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NUMERICAL SIMULATION OF THE FLIGHT DYNAMIC PERFORMANCE OF VARIOUS PROJECTILES FOR SNIPER APPLICATIONS

by

F. Lesage

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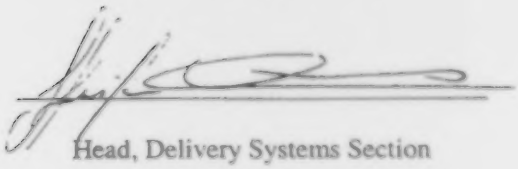
Approved by / approuvé par



Head, Delivery Systems Section
Chef, Section systèmes de lancement

4 August 99
Date

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ABSTRACT

The Directorate of Land Requirements (DLR) has requested the Defence Research Establishment Valcartier to carry out an investigation into the performance of various heavy calibre sniper rifle systems. The objective of this part of the project is to establish with a common simulation methodology the performance aspects related to flight of a wide range of projectiles and to assess their relative importance. A total of fourteen projectiles distributed through four calibres (7.62 mm NATO, .300 Winchester Magnum, .338 Lapua Magnum and 0.50 cal.) were investigated. The geometry and mass properties of the various projectiles were measured. Then, these results were used with the PRODAS software to obtain predictions of drop, velocity, kinetic energy, stability, and sensitivity to launch conditions and wind. These predictions indicated that the different design strategies used for the projectiles (combinations of inertial and aerodynamic properties) give different performance characteristics and that no single design gives the optimum characteristics for a sniper projectile at long range.

RÉSUMÉ

Le Centre de recherches pour la défense Valcartier a été mandaté par le Directorat – Besoin en ressources terrestres pour faire une étude de la performance de plusieurs systèmes d'armes de gros calibre pour tireurs embusqués. L'objectif de cette partie du projet est de déterminer les aspects de performance reliés au vol d'une gamme de projectiles en utilisant une méthode de simulation commune et d'évaluer leurs importances relatives. On a étudié quatorze projectiles distribués en quatre calibres (7,62 mm OTAN, .300 Winchester Magnum, .338 Lapua Magnum and 0.50 cal.).On a mesuré la géométrie et les propriétés massiques des différents projectiles. Ces résultats ont ensuite été utilisés avec le logiciel PRODAS pour obtenir des prédictions de la baisse, la vitesse, l'énergie cinétique, la stabilité et la sensibilité aux conditions de lancement et au vent. Ces prédictions ont indiqué que les différentes stratégies de conception utilisées pour les projectiles (combinaisons des propriétés inertielles et aérodynamiques) donnent différentes caractéristiques de performance et qu'aucun concept ne présente toutes les caractéristiques optimales pour un projectile tiré à longue portée.

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EXECUTIVE SUMMARY

The continuing evolution and concomitant proliferation of protective body armour reduces the capability of the current 7.62 mm NATO calibre sniper rifle in service with the Canadian Forces (C3A1) to defeat targets. To resolve the limitation of the 7.62 mm NATO in a sniper role, many military powers in the world are now using Heavy Calibre Sniper Weapon Systems (HCSWS), the most popular being probably the .50 cal Barret. HCSWS are now capable of defeating personnel targets with protective body armour at long ranges. Furthermore, the larger amount of terminal energy offered by these bullets now makes it possible to assign the sniper an anti-material role. These systems are known to have a good accuracy to at least 1000 meters.

The Directorate of Land Requirements (DLR) has requested the Defence Research Establishment Valcartier (DREV) to carry out an investigation into the performance of various HCSWS recently developed in terms of their accuracy and penetration capabilities at long ranges, and in terms of flash, blast and recoil. This memorandum covers only one aspect of this project, which is the flight dynamics simulation of sniper projectiles of various calibres. The objective is to establish with a common methodology the performance aspects related to the flight of a wide range of projectiles and to assess their relative importance.

A total of fourteen projectiles distributed through four calibres (7.62 mm, .300 Winchester Magnum, .338 Lapua Magnum and 0.50 cal.) were investigated. They represent a sample of available projectiles in the categories of match, AP and SLAP ammunition. The geometries and mass properties of the various projectiles were measured. Then, these results were used with PRODAS software to obtain predictions of drop, velocity, kinetic energy, stability, and sensitivity to launch conditions and wind. These predictions indicated that the different design strategies used for the projectiles (combinations of inertial and aerodynamic properties) give different performance characteristics and that no single design gives the optimum characteristics for a sniper projectile at long range. The performance characteristics obtained for the 14 projectiles studied are now available as a reference for similar projectiles.

NOMENCLATURE

Abbreviations

AP	Armour Piercing
DLR	Directorate of Land Requirement
DREV	Defence Research Establishment Valcartier
HCSWS	Heavy Calibre Sniper Weapon System
HPBT	Hollow Point BoatTail
PRODAS	PROjectile Design and Analysis System
SLAP	Saboted Light Armour Penetrator

Symbols

A	projectile cross-section area
CA	axial force coefficient
CNA	normal force coefficient slope
CMA	pitching moment coefficient slope
d	projectile diameter
I_x	axial moment of inertia
I_y	transverse moment of inertia
k.e.	kinetic energy
m	mass
M_α	pitching moment
p	spin rate
s	downrange distance
S_g	gyroscopic stability factor
t	time of flight
v	muzzle velocity
W_c	cross-wind velocity
θ_0	angle between projectile and cross-wind velocity vectors
ξ_0	initial yaw rate
4DOF, 6DOF	four and six degree-of-freedom trajectory modelling

1.0 INTRODUCTION

Heavy calibre sniper rifle systems (HCSWS) are now capable of defeating material targets and personnel targets with protective body armour at long ranges. These systems are known to have a good accuracy to at least 1000 meters. Many military powers in the world are now using HCSWS and Canada has an interest in acquiring such systems. The Directorate of Land Requirements (DLR) has requested the Defence Research Establishment Valcartier (DREV) to carry out an investigation into the performance of various HCSWS recently developed in terms of their accuracy and penetration capabilities at long ranges, and in terms of flash, blast and recoil. This memorandum covers only one aspect of this project, which is the flight dynamics simulation of sniper projectiles of various calibres. The objective is to establish with a common methodology the performance aspects related to the flight of a wide range of projectiles and to assess their relative importance.

In parallel to this numerical study, several experiments are in progress. Specifically, there is one to measure the accuracy of several HCSWS at long ranges (800, 1000 and 1200 m). The first phase of this experiment has led to the development of experimental techniques to measure dispersion at long range and to the measurement of some typical characteristics of these systems. A separate report will cover this subject. However, during this experiment, eight different projectiles were fired and radar measurements were obtained. This information was used to validate the current numerical simulation.

The most commonly considered calibres for a HCSWS are the .300 Winchester Magnum, the .338 Lapua Magnum and the 0.50 cal. These three calibres were investigated in addition to the 7.62 mm NATO calibre of the in-service C3A1 rifle. A total of fourteen projectiles distributed through these four calibres were investigated for flight performance. These fourteen projectiles represent a sample of available projectiles in the categories of match ammunition, Armour Piercing (AP) ammunition and Saboted-Light Armour Penetrator (SLAP) ammunition.

The first part of this memorandum describes the various projectiles with their geometries and mass properties. Then, the method used with PRODAS (PROjectile

Design and Analysis System) software (Ref. 1) to obtain the flight dynamic performance is described. Finally, the results in terms of drop, velocity and kinetic energy as a function of range and time of flight, as well as in terms of stability and sensitivity to launch conditions and wind are presented and analyzed.

This work was carried out between May and November 1998 under TNS 2na17, "Sniper Recoil and Flash Reduction of Large-Calibre Rifles".

2.0 DESCRIPTION OF PROJECTILES

Several projectile types are of interest to the sniper. There is no single projectile design that can meet all the optimum characteristics. In general, a sniper wants a projectile that is accurate on the first shot, that has a certain penetration level at long range, that has a low sensitivity to wind and that does not have an excessive drop (Ref. 2). It is not possible to have a projectile that will have the best performance in all these categories at the same time. The projectile mass, the external shape, the hard or soft metal core all have a very significant impact on the projectile performance.

For the best accuracy, the Match-grade ammunition is available (dispersion normally less than one minute-of-angle). It is normally a full-metal jacket ball ammunition that is manufactured with very tight tolerances. The bullet weights are normally kept within 0.2 grains (.0013 g)[1] and the jacket wall concentricity within .008 mm. The external configuration includes a long ogive and a boatail for minimum drag. The Armour-Piercing (AP) projectiles have an external shape similar to normal metal-jacketed ball rounds. However, instead of a lead core, it contains a hard metal penetrator. These rounds have a better penetrating capability than the ball projectiles. They do not normally have the close tolerances of the Match-grade ammunition. The Saboted Light Armour Penetrator (SLAP) is another specialty ammunition. It contains a tungsten dart that is mounted in a sabot that is discarded right after launch. Finally, another type of ammunition that can have an interest to

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[1] In the field of small caliber projectiles, the mass unit of grain (gr) is often used instead of grams (g) (1 g = 15.43 gr).

the sniper is the so-called "bush-buster" projectile. It is a stubbier, round-nose type projectile that can cause more damage against a target at close-range.

For this investigation, a total of fourteen projectiles were simulated as indicated in Table I. Three of these projectiles were of 0.50 cal, two of calibre .338 Lapua Magnum, one of calibre .300 Winchester Magnum, and eight of calibre 7.62 mm NATO. All these projectiles were available at DREV at the beginning of this investigation. The match ammunition projectiles #4, 6, 7, and 8 had been acquired for the dispersion tests while the match ammunition projectiles #9 and 10 were already at DREV for terminal ballistics tests. The .50 cal ball (#2) is the Canadian Force ammunition for the Heavy machine gun. The remaining ammunitions are either AP or SLAP ammunitions that were already at DREV for terminal ballistic testing. As was determined by the investigation, not all these projectiles are suitable for long range firing. It was however interesting to compare projectiles with significantly different design in terms of their flight characteristics.

A few samples of each projectile were sent to the DREV metrology laboratory. For each type, the internal and external dimensions were measured. The mass, center of gravity and moments of inertia (axial and transverse) were measured. The accuracy of the mass measurements is expected to be of the order of 1 grain (.065 g) while the accuracy of the moments of inertia is expected to be of the order of 3%. The results are shown Table II and drawings of the projectiles are shown in Figs. 1-14.

In the following sub-sections, a short description of the characteristics of each projectile is given.

2.1 Anthena .50 Calibre PPI

This projectile (Fig. 1) is an armour piercing projectile. It consists of a hard steel penetrator embedded in a brass rear "guide" with a wavy profile that catches the barrel grooves only by its guiding crests. The crests are designed to limit friction points thus reduce barrel wear. It is used by the French Army and police forces. It is produced in France by Anthena.

2.2 .50 Calibre M33

This projectile (Fig. 2) is a full-metal jacket ball ammunition with a steel core. It is designed with a boat-tail. It is the in-service ammunition with the Canadian Forces for the Heavy Machine Gun.

2.3 Olin .50 Calibre SLAP

This is a Saboted Light Armor Penetrator (Fig. 3). It is designed to be effective against vehicle targets at long ranges (up to 2000 m). The sabot is discarded at launch and only the penetrator flies to the target. The projectile (penetrator) has a conical nose and a flat base. The projectile (sabot and penetrator) is lighter than the other two above, and therefore has a muzzle velocity much higher which provides a large amount of kinetic energy at long ranges.

2.4 .338 Lapua Mag Lock Base 16.2g B408

This projectile (Fig. 4) is a full metal jacket ball ammunition with a lead core. Lapua claims that their Lock base design, which refers to the shape of the projectile base, gives superior accuracy at long ranges and guarantees a flat trajectory.

2.5 .338 Lapua Forex 16.8g EX482

This projectile (Fig. 5) is a hunting bullet with a hollow rear chamber which is specially developed for hunting situations in bushes. Lapua claims that, because of its centre of gravity in the front part, it enables a straight trajectory and a low sensitivity to obstacles on the flight path. This projectile is not designed for firing at long ranges.

2.6 .300 Winchester Magnum 190gr. Sierra Match King

This projectile (Fig. 6) is manufactured by Sierra and assembled by Federal. It is a full-metal jacket match ammunition with a lead core. It is called BTHP for Boat-Tail Hollow Point. It is not however a true hollow point which deforms upon impact. The small hole in the nose tip is there only for manufacturing purposes.

2.7 7.62mm 175gr. Sierra Match King

This projectile (Fig. 7) is similar in shape and construction to the .300 Winchester Magnum Sierra Match King. This projectile weighs 175 gr. compared to 190 gr. for the Winchester Magnum.

2.8 Norma 308 Win Match 168gr. HPBT

This is the in-service projectile for the Canadian Forces C3A1 sniper rifle (Fig. 8). It is a full-metal jacket match ammunition with a lead core. It is designed with a boat-tail.

2.9 Norma 308 Win Match 168gr. Diamond

This projectile (Fig. 9) resembles very much the other Norma projectile described above (2.8). It is however slightly different, with a different position of the centre of gravity and a different external finish. The Diamond projectile is covered with a lubricant and a protective layer of wax which result, according to Norma, in a better accuracy, less fouling, easier cleaning and less barrel wear.

2.10 .308 Win HPS Lock base 11g B476

This projectile (Fig. 10) is similar in shape and construction to the Lapua Magnum Lock base B408 described above, except that the calibre is smaller.

2.11 7.62mm AP Bofors Carl Gustaf (M993)

The Bofors Carl Gustaf projectile (Fig. 11) is designed for penetration of hard targets such as light armoured vehicles. The tungsten core gives a high penetration while the soft jacket is designed to provide matched ballistics to standard NATO Ball ammunition and to reduce barrel wear. It is designed for assault rifles and machine guns but not long range firings. The projectile does not have a boat-tail which is a standard design for long range projectiles.

2.12 AP P80 7.62mm NATO

This is an armour piercing projectile (Fig. 12) with a core made of two parts, steel for the front one and lead for the rear one. The jacket is made of a soft metal. This projectile has a boat-tail.

2.13 Anthena PPI 7.62mm NATO

This projectile (Fig. 13) is similar in construction to the 0.50 calibre PPI described above. The exact shape of the ogive and that of the boat-tail are however different. This projectile is designed as an armour piercing round.

2.14 7.62mm SLAP XM948

This projectile (Fig. 14) is a Sabot Light Armour Penetrator for the 7.62 mm rifle from Olin-Winchester. The core, which is the flight projectile, is made of tungsten carbide and weighs only 4.04 g. The projectile shape (cone, cylinder and flat base) indicates that it is not optimised for aerodynamics. This projectile was designed for sub-machine gun use so accuracy was not an important factor in its development.

3.0 PRODAS CALCULATIONS AND VALIDATION

PRODAS (PROjectile Design and Analysis System) is a commercial software (Ref. 1) for projectile ballistic analysis. It is known to have been used to design some of the worlds most accurate and effective projectiles. It can describe a projectile with up to 150 elements, compute the total mass and moments, analyse the aerodynamics and stability of the projectile in flight and predict its dispersions.

Two options exist for the trajectory simulations: the four degree-of-freedom simulation (4DOF) where the yawing and pitching motions of the projectile are neglected, and the six degree-of-freedom simulation (6DOF) where all degrees of freedom are included. For most simulations of sniper projectiles, the 4DOF option is preferable as it gives a result equivalent to that of the 6DOF option in less time.

From each description of projectile obtained from the metrology laboratory, a geometric description of the projectile was entered into PRODAS. The different components were given an estimated density. Based on this information, PRODAS provided a mass, a centre of gravity position and moments of inertia for each projectile. These predicted values were then compared to the measured values and they were found to match those within a few percent. As an example, the measured mass and transverse moment of inertia of the Norma HPBT were 168 gr and 551 $g*mm^2$ while the computed values were 171 gr and 577 $g*mm^2$. The computed values were then replaced by the measured values as they were more accurate.

The aerodynamic coefficients were then calculated by PRODAS. The main coefficients of interest, CA, CNA and CMA are shown in Table II for the Mach 2.0 (680 m/s) flight condition. With the exclusion of the Forex and the two SLAP ammunitions, the axial force coefficient (CA) varies between 0.273 and 0.344. The Forex projectile,

due to its blunt shape has a very high axial force coefficient (0.890), which makes it suitable only for short range. The two SLAP ammunitions have higher axial force coefficients (0.374 and 0.443) due to the absence of a boatail. The normal force coefficient slope (CNA) in very consistent for all the projectiles with the exception of the Forex. It varies between 2.72 and 2.99. For the Forex, due to its different shape, it has a value of 3.46. The pitching moment slope, which is important for stability, varies more than the normal force coefficient. This is due to the fact that this coefficient is not only due to the aerodynamics but also to the point of application of this moment, which is the centre of gravity of the projectile. For instance, the two Norma projectiles have similar external geometry but different position of the centre of gravity. It results that CA and CNA are very close while CMA is significantly different. As will be discussed later, a large CMA is good for a low sensitivity to launch conditions, while a small CMA is good for gyroscopic stability.

Finally, trajectories were simulated using the measured mass properties and the aerodynamic coefficients calculated. The PRODAS 4DOF trajectory simulation package was used for these computations. In a first step, the velocity histories obtained with PRODAS were compared with those measured at the DREV precision range with a Doppler radar in June 98 (Figs. 15-16). Eight projectiles could be verified that way. The quadrant elevation and muzzle velocity measured during the experiment were used for the computations.

Figures 15-16 shows an excellent agreement between the measured and the predicted velocities for six of the eight projectiles. The agreement for the last two, the 7.62 mm PPI and the 7.62 mm SLAP, is not as good but is still reasonable. Discrepancies in bullet mass, aerodynamics, or an important yawing motion of the fired round could be possible causes for the difference which is of the order of 10%. Such a level of accuracy is however sufficient for the type of analysis of this report where projectiles of different designs are compared to study the influence of the main design aspects.

4.0 PREDICTION RESULTS

Following the validation with the radar measurements, PRODAS was used to predict the flight performance aspects of each of the fourteen projectiles. For each calculation, the simulation was made using a quadrant elevation of zero and an altitude of 25 meters. This altitude was chosen so that no projectile will impact the ground before a range of 1200 m. The muzzle velocity used in the simulation was obtained either from radar measurements when available (eight projectiles of Figs. 15-16), or from published supplier information. The following values to a range of 1200 m were obtained:

- time of flight
- velocity
- kinetic energy
- density of kinetic energy
- drop
- wind sensitivity

Other performance aspects of each projectile, such as the sensitivity to the initial yawing rate at muzzle exit and the transonic range, were also predicted by PRODAS.

4.1 Gyroscopic Stability

The gyroscopic stability of the projectiles was examined. For a spin-stabilised projectile, the gyroscopic stability factor determines whether a projectile is gyroscopically stable or not. This factor is defined as:

$$S_g = \frac{p^2 I_x^2}{4 M_\alpha I_y} \qquad [1]$$

If the gyroscopic stability factor is greater than one, the projectile is gyroscopically stable. Normally, this factor should be between 1 and 2.5 for all flight conditions. From the definition of the gyroscopic stability factor, it can be observed that the spin rate and the axial moment of inertia have to be high while the pitching moment and the transverse moment of inertia have to be small. During flight, the spin rate will drop due to spin damping and the pitching moment may rise in the transonic regime. The spin rate must therefore be high enough at the muzzle to keep

the dynamic coefficient above 1 for the whole trajectory. For the projectiles under investigation, the gun twist was selected to maintain gyroscopic stability throughout the trajectory. As the twist for the C3A1 gun (in-service CF 7.62 mm sniper rifle) is 39 calibres per turn, it was used for most of the 7.62 mm ammunition. Two of them, both AP rounds, were not stable through the whole flight with this gun twist. They became unstable towards the transonic range. For these two, the twist was changed to 35 calibres per turn (faster spin) which is a twist commercially available. For the larger calibre ammunition, the twist was kept at 35 calibres per turn which was just sufficient to maintain gyroscopic stability.

The effect of gun twist was not examined in this investigation and care was taken to ensure gyroscopic stability throughout the flight. However, the fact that this brief analysis showed that some projectiles became unstable with certain gun twist indicates that gun twist is critical to the weapon/projectile system. It is obvious that, as soon as a projectile becomes unstable, it is inaccurate.

4.2 Velocity

The muzzle velocity for a projectile of a given calibre is largely a function of its mass. The heavier the projectile, the lower its muzzle velocity will be in general because there is a fixed amount of propellant energy available. The velocity decay, or retardation, of a projectile, on the other hand, is mainly a function of its mass and its drag coefficient. A high mass or a low drag coefficient results in a low retardation.

The projectile velocity as a function of range is given in Fig. 17 for the fourteen projectiles of the study. The results are split in four groups for clarity.

The fastest projectiles are the two SLAP projectiles (0.50 cal and 7.62 mm). This is because the SLAP projectiles are much lighter than their ball or AP counterparts. Because of the sabot that separates from the penetrator during the early stage of flight, this type of projectile is however not expected to be as accurate as the ball or AP projectiles.

For the 0.50 cal projectiles, the retardation is similar for all three. The 0.50 ball (M33) projectile is the slowest, but still has a velocity of 400 m/s at 1200 m. The

0.338 Forex has a very high drag which slows down this projectile very rapidly. This projectile is designed for very short ranges and should therefore not be considered for long ranges. It is of little interest to this study except to show a typical extreme case. It will not be discussed further. The .300 Winchester Mag. has a higher muzzle velocity than the .338 Lapua Mag., but because it is lighter its velocity decays faster. The two projectiles have similar velocities at 1200 m (around 400 m/s).

Examination of the eight 7.62 mm results leads to the following observations. The match projectiles studied were heavier than the the AP projectiles (~11 g vs ~9 g). These projectiles therefore had a lower muzzle velocity than their AP counterparts (~15% lower). However, since they were heavier, their retardation was smaller and at 1200 m, the match projectiles were in general slightly faster than the AP projectiles. All projectile velocities were in the neighbourhood of 300 m/s at 1200 m. The AP Bofors, which has the smallest mass of the AP rounds and a high drag coefficient, has the lowest velocity of all at 1200 m. Although the 7.62 mm SLAP had a much higher muzzle velocity because of its small mass, its velocity dropped to a level even below that of most other projectiles at 1200 m. This round has therefore lost its kinetic energy advantage at 1200 m. The Sierra match is the 7.62 mm projectile with the highest velocity at 1200 m, i.e. 310 m/s.

4.3 Time of Flight

The time of flight (Fig. 18) may be important for moving targets. The shortest time of flight is 1.3 s to reach 1200 m for the 0.50 cal SLAP. The remaining 0.50 cal projectiles, the .338 Lapua Mag. and .300 Winchester Mag. projectiles all have a time of flight of about 2 s at 1200 m. The .338 Forex is off-scale and it is not further considered for the reasons presented in the previous sub-section. All the 7.62 mm have a time of flight in the range of 2.4 to 2.8 s. The shortest times of flight for this calibre are obtained by the PPI and the SLAP.

4.4 Gravity Drop

This aspect is important, as the larger the gravity drop, the higher the quadrant elevation has to be to hit the target. As the interest is in long ranges, the drop can be significant. Fig. 19 shows the gravity drop for the fourteen projectiles. The trends between projectiles are identical to that of the time of flight as these two are directly related. The drop for the 0.50 cal ball is of the order of 15 m while the drop for the 7.62 mm projectiles is of the order of 25 m.

The effect of range estimation error can be obtained from this Figure. For instance, Fig. 19 indicates that an error of 20 m in range estimation at 1000 m would result in an error in drop of 99 cm for the 7.62 mm Bofors and in an error of 21 cm for the 0.50 cal SLAP. The faster projectile has therefore a significant advantage. The range estimation is one of the most important source of error for the sniper.

4.5 Kinetic Energy

The kinetic energy (k.e.) is a measure of the energy that can be delivered to a target. For instance, the best personnel protection (jacket with armour plate) is expected to currently offer a protection against impacts of the order of 4 KJ, which is the energy delivered at the muzzle by a 7.62 mm AP round (Ref. 3). The kinetic energy is defined as:

$$k.e. = \tfrac{1}{2} m v^2 \qquad [2]$$

Figure 20 shows the kinetic energy for the fourteen projectiles of this investigation. Only the 0.50 cal projectiles meet the 4 KJ level at 1200 m. The .338 Lapua Mag will have this kinetic energy at 400 m and the .300 Winchester Mag at 250 m. Most of the 7.62 mm projectiles do not have this kinetic energy even at the muzzle. Of the 7.62 mm projectiles studied, only the P-80 has this kinetic energy at the muzzle. However, if the requirement is for less kinetic energy, the different calibres could be of interest.

At long range, the 0.50 cal SLAP has the most kinetic energy, while the 7.62 mm SLAP has the least. Most of the 7.62 mm projectiles (all except the SLAP and Bofors) deliver a similar k.e. as a function of range.

4.6 Density of Kinetic Energy

Fig. 21 gives the density of kinetic energy as a function of range for each projectile. It is defined as follows:

$$\text{density of k.e.} = \frac{\text{k.e.}}{\text{A}} \qquad \text{where A is the projectile cross - section} \qquad [3]$$

This is the important aspect to consider for armour penetration. This performance aspect shows the advantage of the SLAP projectiles. Because they are sub-calibre projectiles, their small core diameters provide more density of kinetic energy. The 7.62 mm SLAP however loses this advantage at long range. For this performance aspect, the .338 Lapua Mag and the .300 Winchester Mag. have similar values. The 0.50 cal ball has almost twice the value of the .338 Lapua Mag. or .300 Winchester Mag. and four time the value of the 7.62 mm projectiles at 1200 m.

4.7 Wind Drift

A cross wind of 4.47 m/s (10 MPH) was simulated in PRODAS. The horizontal cross range position of the projectile was subtracted from that of the projectile for the no wind condition (drift due to projectile spin). This horizontal position as a function of range is shown in Fig. 22 for the fourteen projectiles.

A wind magnitude of 4.47 m/s is a very strong wind for a sniper. As shown in Fig. 22, the projectile will drift in the range of 1 to 7 m depending on the projectile used. This wind magnitude was used as a reference, as the effect of a lower wind velocity is proportional.

The least sensitive projectiles are the 0.50 cal family. Then follows the .338 Lapua Mag and the .300 Winchester Mag which are almost equivalent in value. The wind drift for the 7.62 mm projectiles varies significantly from one projectile to the other (between 5 and 7 m).

The wind drift at 1000 m is given in Table III for all the projectiles. Results from the so-called "Rifleman's formula" are also given. The agreement between the two results is impressive.

"Rifleman's formula" is an approximation to the first order of the effect of a constant cross wind on an adequately stable projectile. It uses the concept of relative velocities. The wind drift is calculated as (Ref. 4):

$$\text{Wind drift} = W_c\left(t - \frac{s}{v \cdot \cos\theta_0}\right) \qquad [4]$$

where W_c is the cross wind velocity

t is the time of flight

$\frac{s}{v \cdot \cos\theta_0}$ is the time of flight in vacuo

s is the range

v is the projectile muzzle velocity

θ_0 is the angle between the velocity vector and the cross wind vector

In this calculation, the value of t (time of flight) is taken from the 4DOF simulation without wind. The good agreement between the two methods indicates that the simpler method (Rifleman's formula) can be used with confidence.

This equation indicates that to get a small sensitivity to wind a projectile should have a small difference between the actual time of flight and the time of flight in vacuo. To achieve this, a projectile must have a high muzzle velocity and a small velocity drop (small drag coefficient and large mass).

As high muzzle velocity is conflicting with a large mass, it is a matter of compromise. The Sierra, HPS and PPI all have very similar low cross-wind sensitivity with different values of mass, muzzle velocity and drag coefficient (see Table II). The Bofors with a small mass, and high CA (but with a high muzzle velocity) is the most sensitive to cross-wind.

4.8 Sensitivity to Launch Conditions

The yawing motion of a projectile accounts for a portion of the deviation from the point of aim. This yawing motion is mainly due to an initial yawing rate provided to the projectile at shot exit. It is the result of the in-bore ballotting motion and shot disengagement process.

The yawing motion may lead to dispersions due to yaw drag. This mechanism is important with indirect fire ammunition. For direct fire rounds however, it is mainly the heave and swerve due to the yawing rate that are large contributors to dispersion. To describe this motion, a calculation with the 6DOF trajectory module of PRODAS, which includes the yawing and pitching motions, was carried out for the 0.50 cal Ball M33. Fig. 23 shows the swerve motion (projectile centre of gravity motion in the horizontal plane) of the projectile for yaw rates of 0 and 25 rad/s. A small drift occurs for the zero yaw rate due to the projectile spin. The yaw rate of 25 rad/s induces a significant projectile motion which is damped out within about 200 m of the trajectory as indicated in Fig. 23. Once the effect of the initial yaw rate is damped out, the projectile flies towards the target with a constant angular error. This error is often called the aerodynamic jump. In this case the offset between the two curves is 0.375 mrad.

Instead of performing the 6DOF trajectory simulations, it is possible to obtain, with proper simplifications of the equations of motion, a simple equation (Ref. 4) giving the deviation at the target as a function of mass properties, aerodynamic coefficients, velocity, range and yawing rate:

$$\text{deviation} = \frac{I_y \, CNA}{m \, v \, d \, CMA} \dot{\xi}_0 \, s \qquad [5]$$

As the yawing rate is not known, the deviation is given as function of yawing rate units (mrad / (mrad/s)):

$$\frac{\text{deviation}}{\dot{\xi}_0 \, s} = \frac{I_y \, CNA}{m \, v \, d \, CMA} \qquad [6]$$

A slightly more complex equation is included in PRODAS. Results from both equations are given in Table III. The agreement between the two is excellent.

Equation [6] indicates that CMA, m, v should be large and I_y and CNA should be small for a small sensitivity to yawing rate. As seen in Table I, CMA is more variable than CNA from one projectile to the other, and therefore its value is quite responsible for this sensitivity.

It is the 0.50 cal PPI, the 0.50 cal. Ball and the 7.62 mm Norma Diamond that have the largest sensitivity to yawing rate. The 7.62 mm AP bofors and the Norma HPBT have the lowest sensitivity. No specific term of the equation seems to play a more dominant role than the others on the sensitivity. It is really a combination of all terms.

The initial yawing rate will depend on the rifle/projectile system. For this investigation, no specific information on the initial yawing rate were specifically obtained. However, some recent Aeroballistic Range firings (Ref. 5) indicate that the initial yaw rate for the M33 could be of the order of 25 rad/s. In addition, some terminal ballistic measurements (Refs. 6 and 7) indicated an angle of attack of 2 to 3 degrees at a range of 20 m obtained for 7.62 mm projectiles such as the AP Bofors. This result translates into a yawing rate of about 50 rad/s at the muzzle. A value of yawing rate between 0 and 50 rad/s can therefore be expected for the projectiles under investigation. For the M33, a yawing rate of 25 rad/s translates into a deviation at 1200 m (based on the result of Table III) of:

0.0151 mrad/rad/s * 25 rad/s * 1200 m / 1000 rad/mrad = 0.453 m

This value (0.453 m /1200 m = 0.377 mrad) compares well with the value from the 6DOF simulation (0.375 mrad) indicating that the simple equation gives a good representation of the overall effect.

It is clear that the deviation due to the yaw rate can be significant. The yawing rate was however not characterised in this investigation. As Match ammunition have tight tolerances, one would expect that the initial yaw rate for these projectiles is much lower. This still needs to be verified however.

4.9 Transonic Range

These projectiles are designed to fly supersonically. When they reach transonic speeds (near Mach 1.0), the aerodynamic coefficients vary significantly and the projectiles often start becoming unstable. The transonic range is easily determined by the simulation as the range at which the projectile flight Mach number becomes one. These range values are given in Table III and can serve as a guide to the maximum range of a projectile.

The 7.62 mm projectiles have a transonic range between 780 and 980 m, while the 0.50 cal SLAP has a transonic range of 2600 m.

4.10 Overview of the Results

A summary of the results is presented in Table III and in Figs. 24-25. Table III gives the numerical values of each performance aspect at 1000 m. It is useful to compare the different performance aspects of the different projectiles. Figs. 24-25 give graphically the different performance aspects for one projectile of each calibre. The selected projectiles are the 0.50 cal ball, the .338 Lapua Mag., the .300 Winchester Mag. and the 7.62 mm Sierra Match King. The significant aspects of these figures have already been discussed in the previous subsections. These figures are however useful to compare the performance of the different calibres.

As it was indicated previously, no single projectile design can meet all the optimum characteristics. The influence of the inertial or aerodynamic characteristics on the various performance aspects were presented in the appropriate subsection. Table IV gives a summary of the effect of the inertial and aerodynamic properties on the performance aspects. This Table indicates that there are conflicting requirements. For example, a high projectile mass is good for high kinetic energy, short time of flight and low sensitivity to launch conditions. On the other hand, it is detrimental to achieve a high muzzle velocity. Another example is the conflicting requirement for CMA. A high CMA will minimise the effects of launch conditions but will increase the sensitivity to cross-wind.

5.0 DISCUSSION

This study is an initial phase in the investigation on the overall performance of various Heavy Calibre Sniper Weapon Systems. A lot of information is available on the performance of sniper projectiles at ranges up to 800 m. There is however very little technical information on the performance of the projectiles at ranges up to 1200 m. The objective of this initial study was therefore to establish, through numerical simulations, the important aspects to consider when evaluating flight performance at long ranges.

This study has indicated that different design strategies (combinations of inertial and aerodynamic properties) give different performance characteristics and that no single design gives the optimum characteristics for a sniper projectile at long range. This study indicated that all the performance aspects investigated need to be closely examined when evaluating HCSWS and the relative significance of the different performance aspects has to be established to identify the best projectile. Most projectiles appear to be advantageous for one performance aspect or another. However, the large calibre projectiles give better overall performance for the aspects investigated. On the other hand, other important performance aspects such as flash, blast, recoil and weapon mass and handling were not considered in this study and may not favour the larger calibres.

The performance characteristics obtained for the 14 projectiles studied is now available as a reference and can be used for projectiles with similar characteristics. The 14 projectiles represent a range of potential projectile designs. Only two of these do not represent the expected performance of long range sniper projectiles: the 7.62 mm Forex and the 7.62 mm SLAP (XM948). All others seem to have at least the minimum qualities required. The Swedish Army is currently working with FMV on a sniper version of the Olin SLAP round which should overcome the deficiencies noted (Ref. 8).

6.0 CONCLUSIONS AND RECOMMENDATIONS

Heavy calibre sniper rifle systems (HCSWS) are now capable of defeating material targets and personnel targets with protective body armour at ranges beyond

1200 m. The Directorate of Land Requirements (DLR) has requested the Defence Research Establishment Valcartier to carry out an investigation into the performance of various HCSWS recently developed in terms of their accuracy and penetration capabilities at long ranges, and in terms of flash, blast and recoil. This memorandum covers only one aspect of this project, which is the flight dynamics simulation of sniper projectiles of various calibres.

A total of fourteen projectiles distributed through four calibres (7.62 mm, .300 Winchester Magnum, .338 Lapua Magnum and 0.50 cal.) were investigated for flight performance. These fourteen projectiles represent a sample of available projectiles in the categories of match ammunition, Armour Piercing (AP) ammunition and Saboted-Light Armour Penetrator (SLAP) ammunition.

In this study, the geometry and mass properties of the various projectiles were first measured. Then, these results were used with PRODAS software to obtain predictions of drop, velocity, kinetic energy, stability, and sensitivity to launch conditions and wind. These predictions indicated that the different design strategies used for the projectiles (combinations of inertial and aerodynamic properties) give different performance characteristics and that no single design gives the optimum characteristics for a sniper projectile at long range. This study indicated that all the performance aspects investigated need to be closely examined when evaluating HCSWS. The performance characteristics obtained for the 14 projectiles studied are now available as a reference for similar projectiles.

The experimental program that is being undertaken under the other phases of this project will indicate for which situation further simulations are required to improve our understanding of the sources of dispersion. For example, this study assumed that all projectiles were gyroscopically stable and neglected the effect of Magnus coefficients which are related to the spinning motion of projectiles. Future studies may include the analysis of these effects if they are considered significant based on the experimental results that will be obtained for this project.

7.0 ACKOWLEDGEMENTS

The author would like to thank Messrs. B. Villeneuve and N. Viel, from the Prototype Group, for the careful measurements of the projectile mass properties and for the production of the drawings representing the components. The work of ELOF L. Roy during his summer project at DREV in 1998 provided the initial direction for this project. Messrs. D. Leclerc and G. Pageau, from the Terminal Ballistics Group, provided assistance in this project through discussions, exchange of information and by supplying the sample projectiles that were used in the analysis.

8.0 REFERENCES

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TABLE I

Description of projectiles

#	Description	Calibre	Source	Type
1	.50 calibre PPI	.50 calibre	Anthena	AP
2	.50 calibre M33	.50 calibre	-	Ball
3	.50 calibre SLAP	.50 calibre	Olin	SLAP
4	.338 Lapua mag Lock base 16.2g B408	.338 Lapua Mag	Lapua	Match
5	.338 Forex 16.8g EX482	.338 Lapua Mag	Lapua	Forex
6	.300 190gr. Sierra match King	.300 Winchester Mag	Federal	Match
7	7.62mm 175gr. Sierra Matchking	7.62mm NATO	Federal	Match
8	Norma 308 Win Match 168gr. HPBT	7.62mm NATO	Norma	Match
9	Norma 308 Win Match 168gr. Diamond	7.62mm NATO	Norma	Match
10	.308 Win HPS Lock base 11g B476	7.62mm NATO	Lapua	Match
11	7.62mm AP Bofors Carl Gustaf	7.62mm NATO	Bofors	AP
12	7.62mm AP P80	7.62mm NATO	FNB	AP
13	PPI 7.62mm	7.62mm NATO	Anthena	AP
14	7.62mm SLAP XM948	7.62mm NATO	Olin	SLAP

TABLE II

Inertial and aerodynamic properties of the projectiles in flight

Projectile	Muzzle velocity (m/s)	Mass (g)	Mass (gr)	Dia. (mm)	Length to diameter ratio	Centre of gravity from nose (cal)	Transverse moment of inertia (g*mm**2)	CA at Mach 2.0	CNA at Mach 2.0	CMA at Mach 2.0	Twist (cal / turn)
.50 cal PPI	890	48.49	748	12.95	4.57	2.68	10272	0.344	2.84	3.11	35
.50 Cal Ball	830	42.06	649	12.95	4.48	2.74	7154	0.293	2.74	2.87	35
.50 Cal Slap	1173	23.00	355	7.72	4.79	2.96	2507	0.374	2.99	3.11	35
.338 Lapua B408	892	16.21	250	8.58	4.40	2.59	1250	0.292	2.78	2.59	35
.338 Lapua Forex	875	16.80	259	8.58	4.46	2.23	1769	0.890	3.46	2.87	35
.300 Win Mag	932	12.53	190	7.82	4.36	2.42	798	0.294	2.79	2.31	35
7.62 Sierra Match	813	11.33	175	7.82	4.06	2.42	610	0.312	2.81	2.32	39
7.62 Norma HPBT	812	10.87	168	7.82	3.89	2.36	551	0.328	2.82	2.14	39
7.62 Norma Diamond	777	10.88	168	7.82	3.93	2.20	579	0.322	2.81	1.61	39
7.62 Lapua HPS	787	11.00	170	7.82	3.98	2.45	595	0.306	2.81	2.24	39
7.62 AP Bofors	950	8.27	128	7.82	3.38	2.30	337	0.349	2.83	2.07	35
7.62 AP P80	905	9.73	150	7.82	4.17	2.45	635	0.343	2.86	2.48	39
7.62 PPI	900	8.85	136	7.82	4.35	2.64	528	0.273	2.72	2.19	35
7.62 Slap XM948	1220	4.04	52.1	3.38	3.68	3.31	88	0.443	2.97	1.55	39

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TABLE III

Performance aspects

Projectile	Time of flight (s) at 1000 m	Velocity (m/s) at 1000 m	Gravity drop (m) at 1000 m	Kinetic energy (KJ) at 1000 m	Density of kinetic energy (KJ/mm**2) at 1000 m	Wind drift (m) at 1000 m	Rifleman's formula (m) at 1000 m	Jump (mrad/rad/s) - equation	Jump (mrad/rad/s) - PRODAS	transonic range (m)
.50 cal PPI	1.47	521.6	8.90	6.597	0.0501	1.502	1.535	0.0168	0.0160	1650
.50 Cal Ball	1.62	464.0	10.66	4.528	0.0344	1.848	1.842	0.0151	0.0130	1460
.50 Cal Slap	1.03	808.3	4.58	7.515	0.1605	0.780	0.780	0.0100	0.0080	2600
.338 Lapua Mag	1.56	464.6	9.65	1.750	0.0303	1.945	1.940	0.0108	0.0100	1396
.338 Lapua Mag Forex	2.65	243.1	24.81	0.496	0.0086	6.741	6.737	0.0169	0.0160	561
.300 Win Mag	1.53	457.3	9.24	1.288	0.0268	2.073	2.065	0.0106	0.0100	1345
7.62 AP Bofors	2.10	282.0	15.01	0.329	0.0068	4.689	4.682	0.0103	0.0090	978
7.62 Norma Match HPBT	2.05	314.5	14.79	0.538	0.0112	3.644	3.636	0.0105	0.0090	891
7.62 Sierra Match	1.94	334.7	14.02	0.635	0.0132	3.190	3.187	0.0153	0.0140	849
7.62 Slap XM948	1.76	303.5	10.04	0.156	0.0086	4.208	4.202	0.0110	0.0100	913
7.62 Lapua HPS	2.04	320.3	15.35	0.564	0.0117	3.343	3.439	0.0075	0.0070	782
7.62 AP P80	1.97	315.5	13.61	0.484	0.0101	3.859	3.856	0.0106	0.0110	881
7.62 PPI	1.84	334.2	12.24	0.494	0.0103	3.266	3.262	0.0105	0.0100	981
7.62 Norma Match Diamond	2.13	307.3	16.63	0.514	0.0107	3.797	3.789	0.0071	0.0050	887

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TABLE IV

Effect of the mass and aerodynamic properties on the performance aspects

	Muzzle velocity	mass	diameter	Iy	CA	CMA	CMA/CNA
Velocity		-			-		
Time of flight	+	+	-		-		
Gravity drop	+	+	-		-		
Kinetic energy	+	+	-		-		
Density of kinetic energy	+	+	-		-		
Wind drift	+	+			-	-	
Launch conditions	+	+		-		+	+
Transonic range	+	+	-		-		
Stability				-		-	

(+ means larger better, - means smaller better)

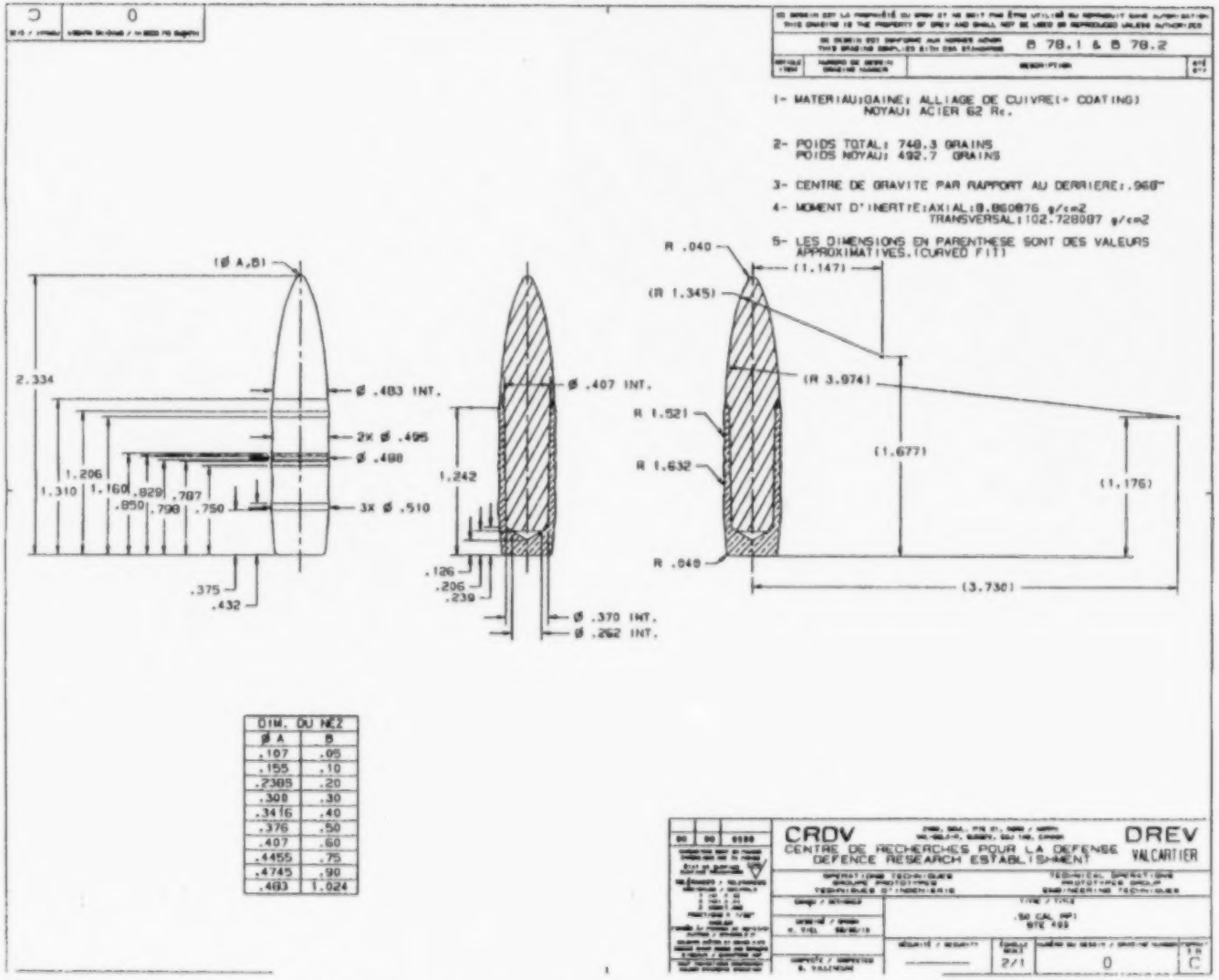

FIGURE 1 – Drawing of Anthena 0.50 Calibre PPI

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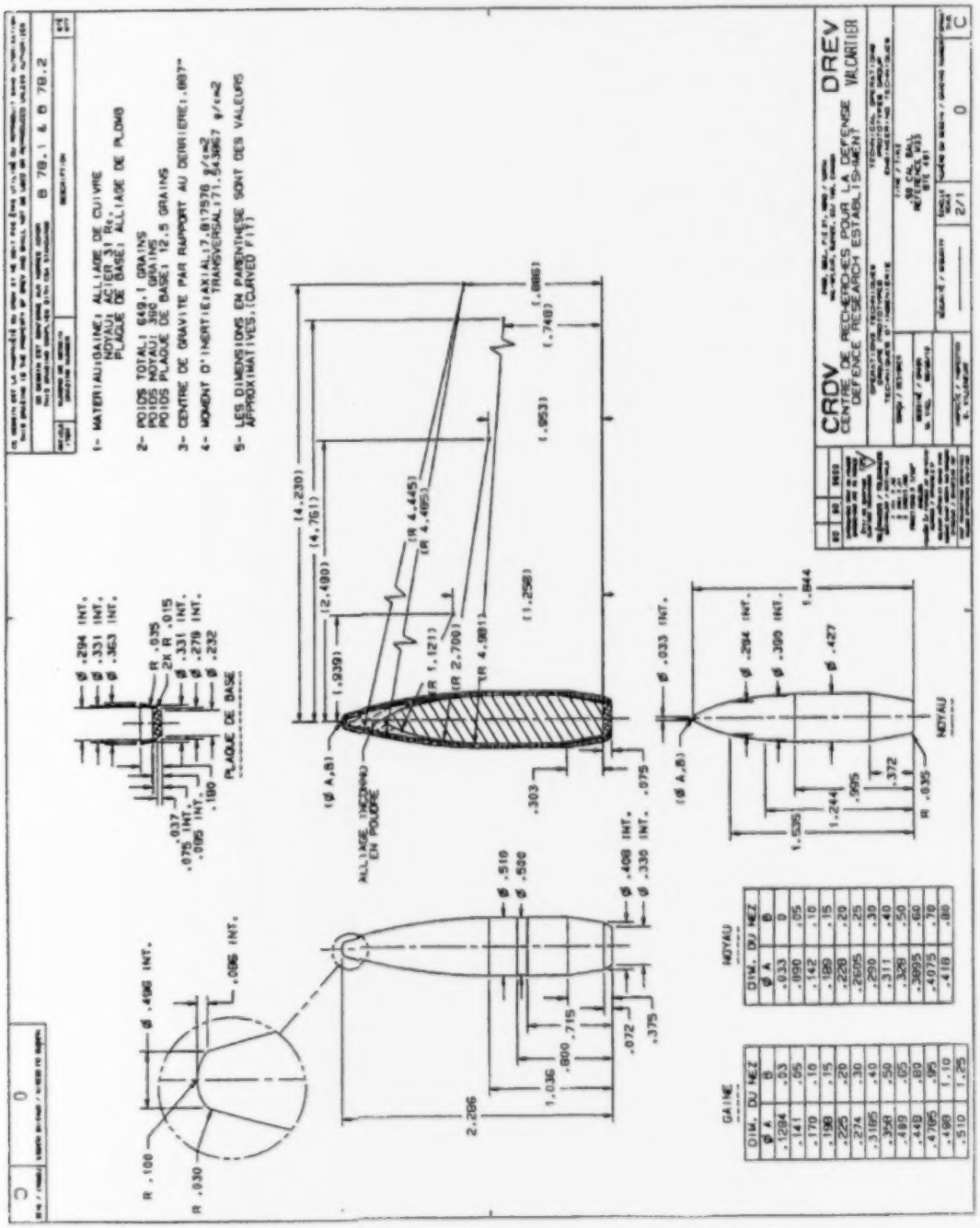

FIGURE 2 – Drawing of 0.50 Calibre M33

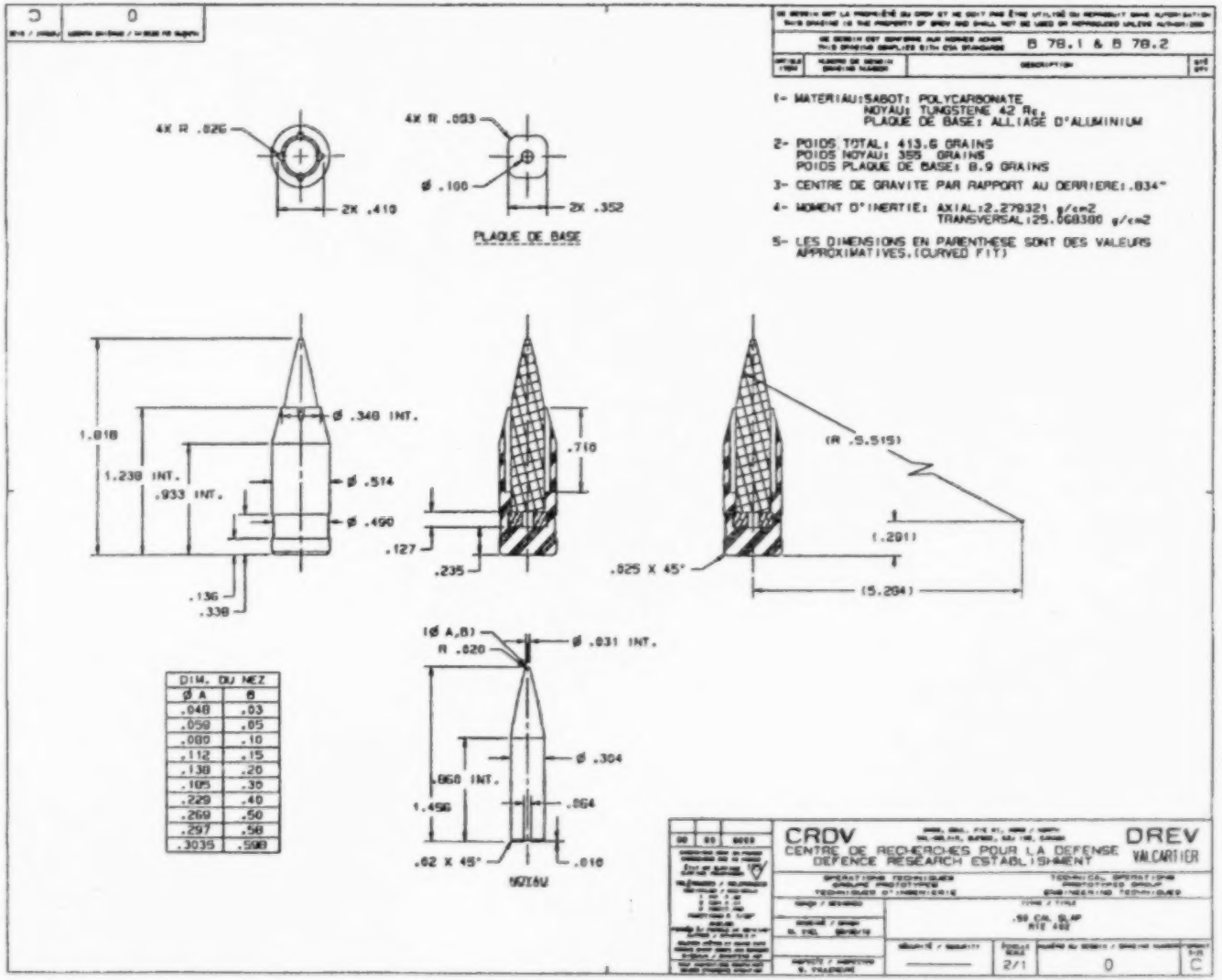

FIGURE 3 – Drawing of Olin .50 Calibre SLAP

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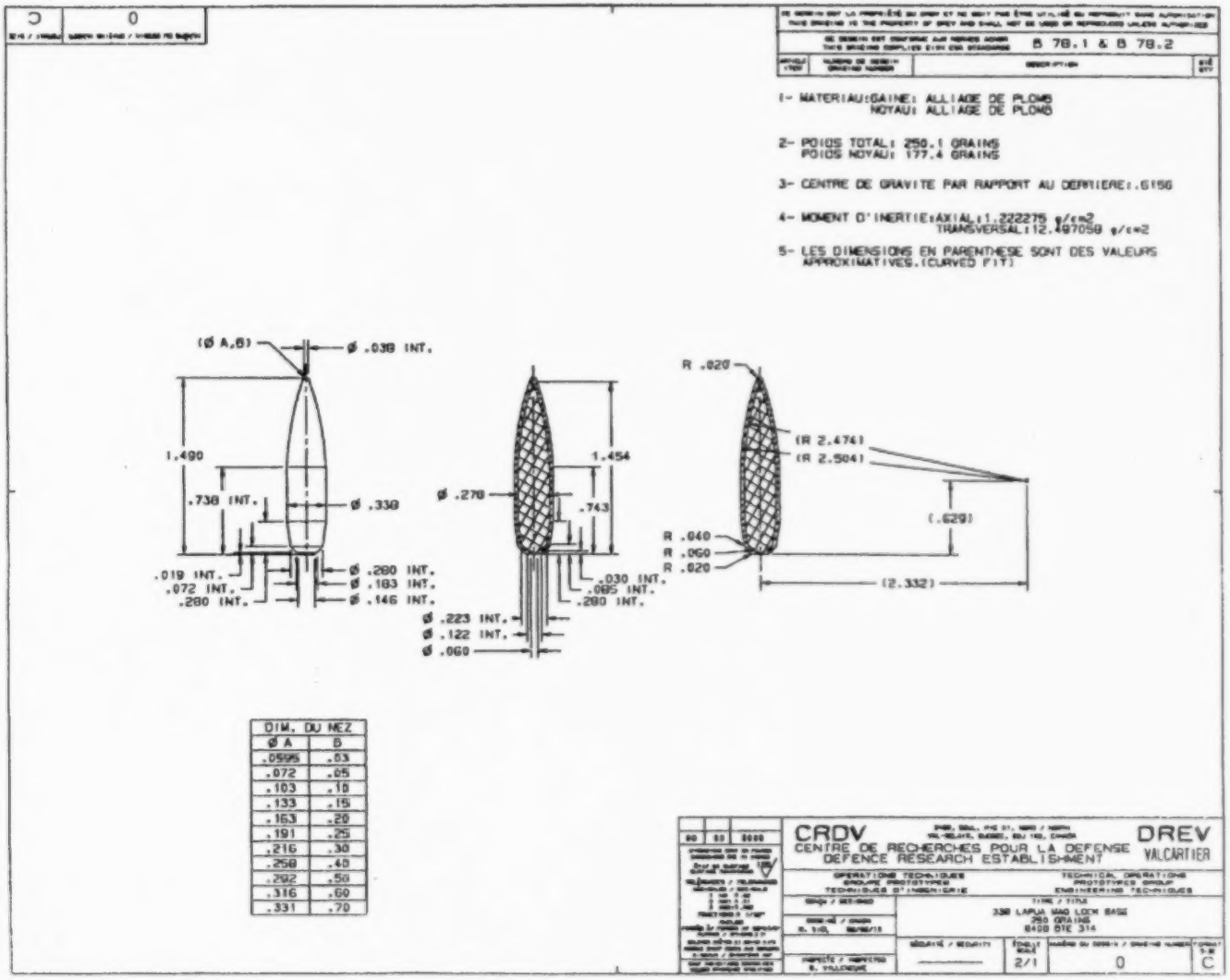

FIGURE 4 – Drawing of .338 Lapua Mag Lock base 16.2g B408

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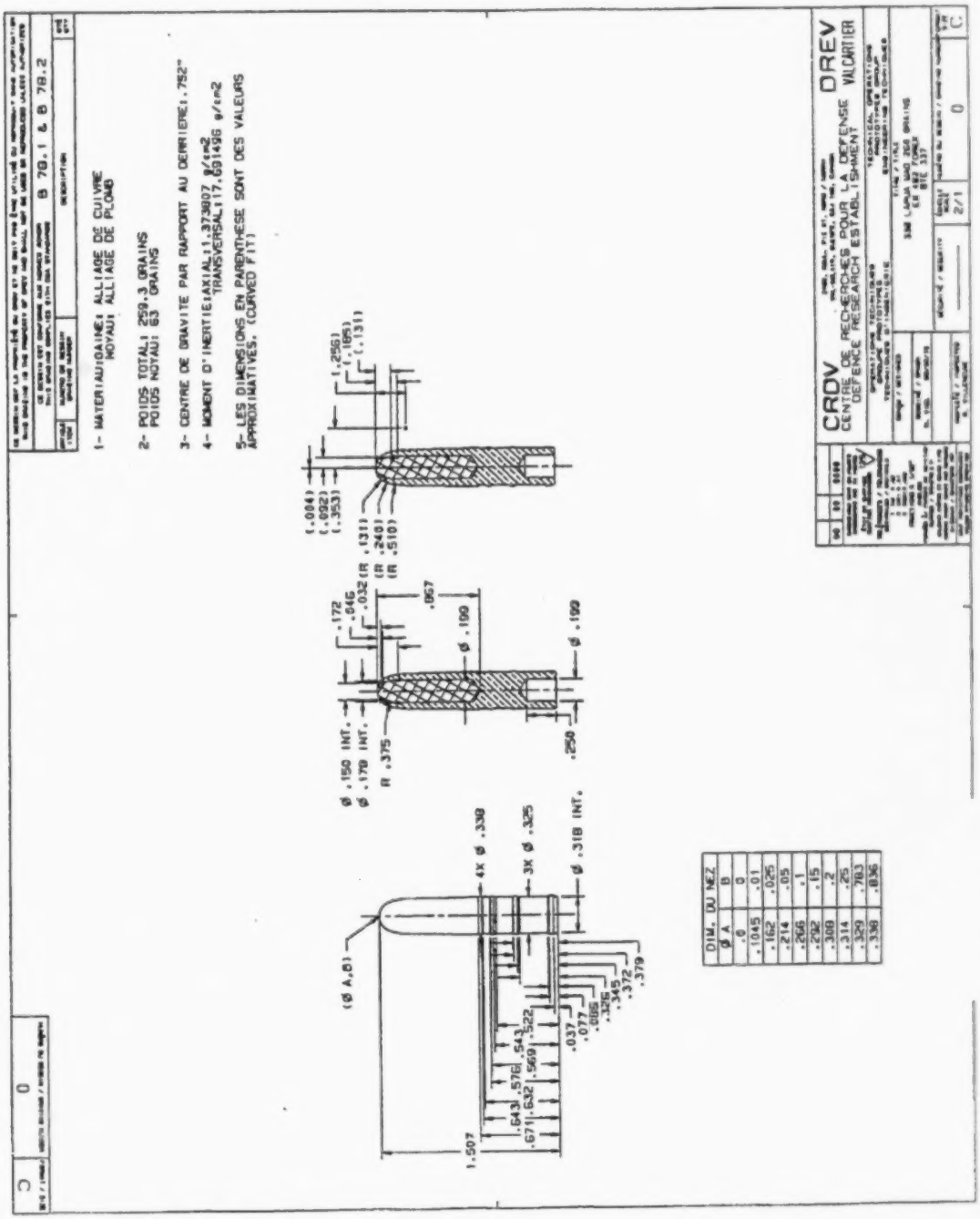

FIGURE 5 – Drawing of .338 Lapua Forex 16.8g EX482

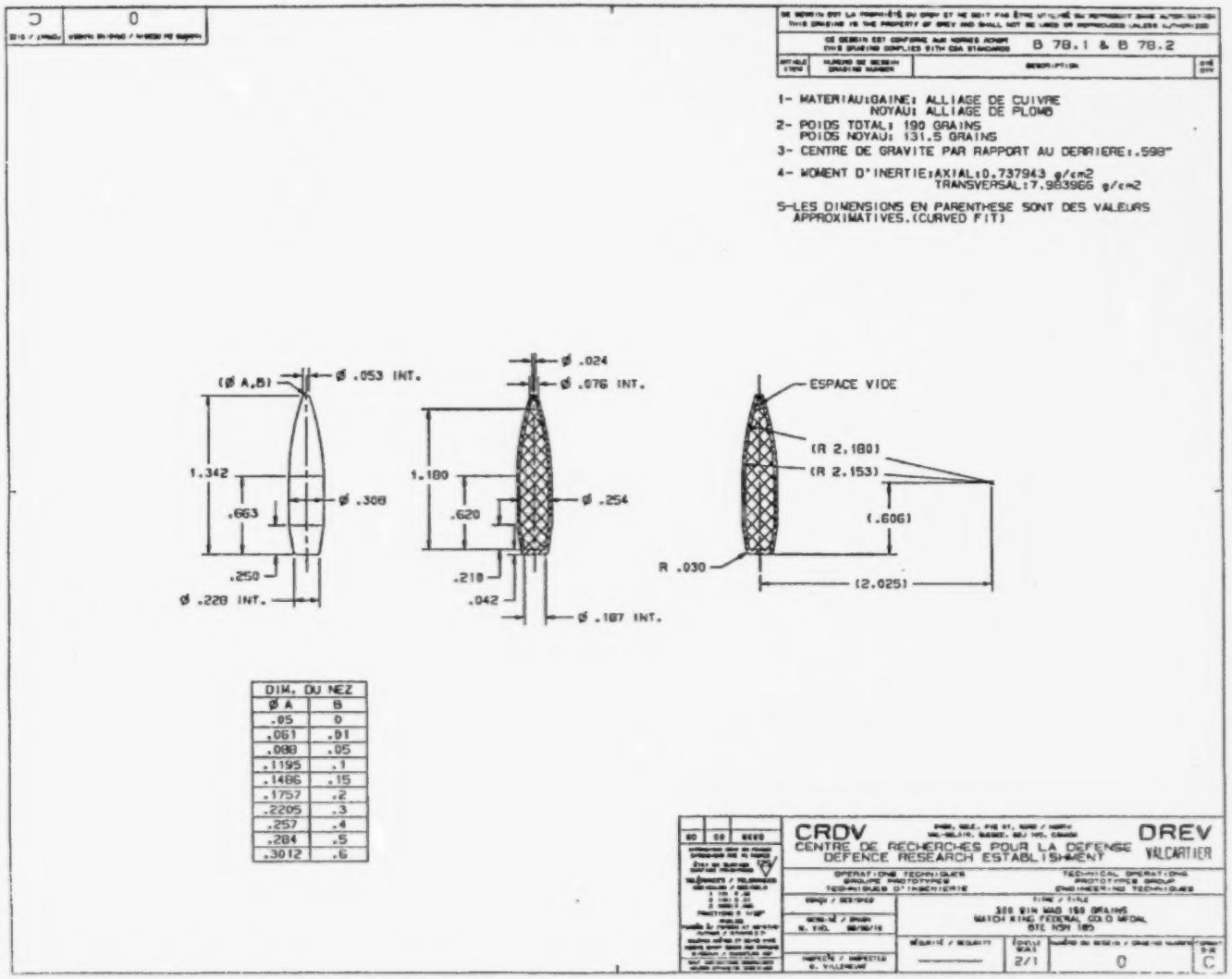

FIGURE 6 – Drawing of .300 Winchester Magnum 190gr. Sierra Match King

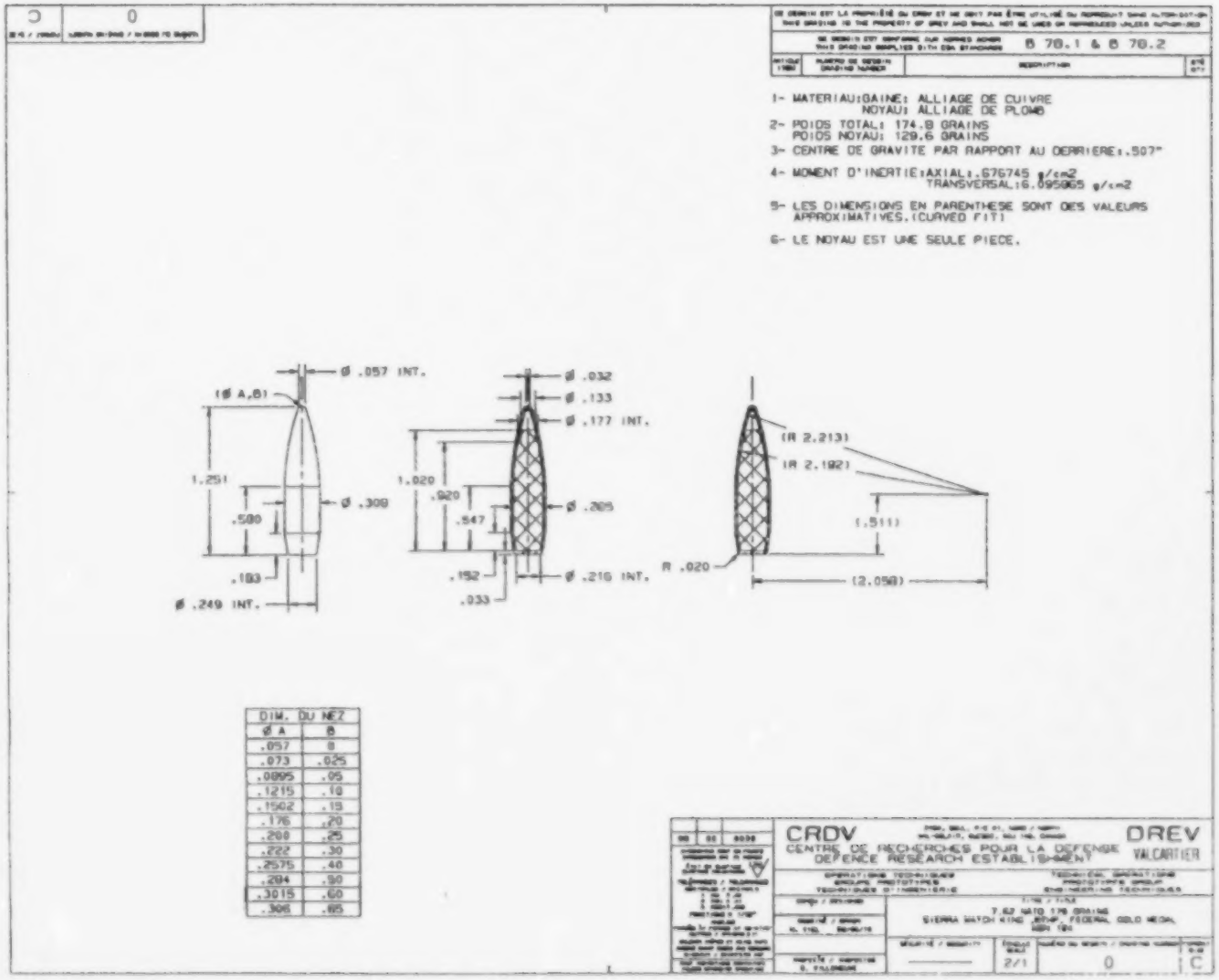

FIGURE 7 – Drawing of 7.62mm 175gr. Sierra Match King

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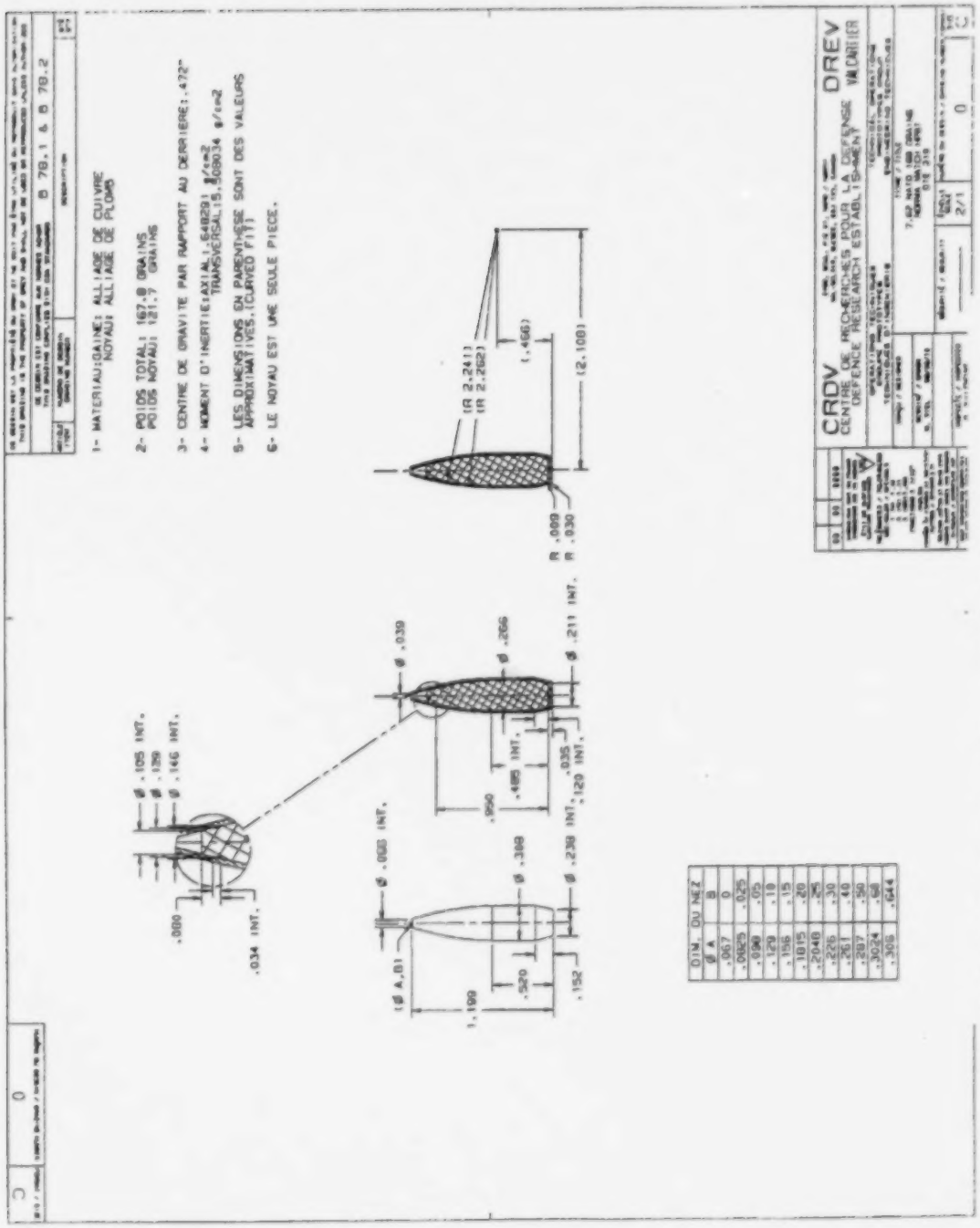

FIGURE 8 – Drawing of Norma 308 Win Match 168gr. HPBT

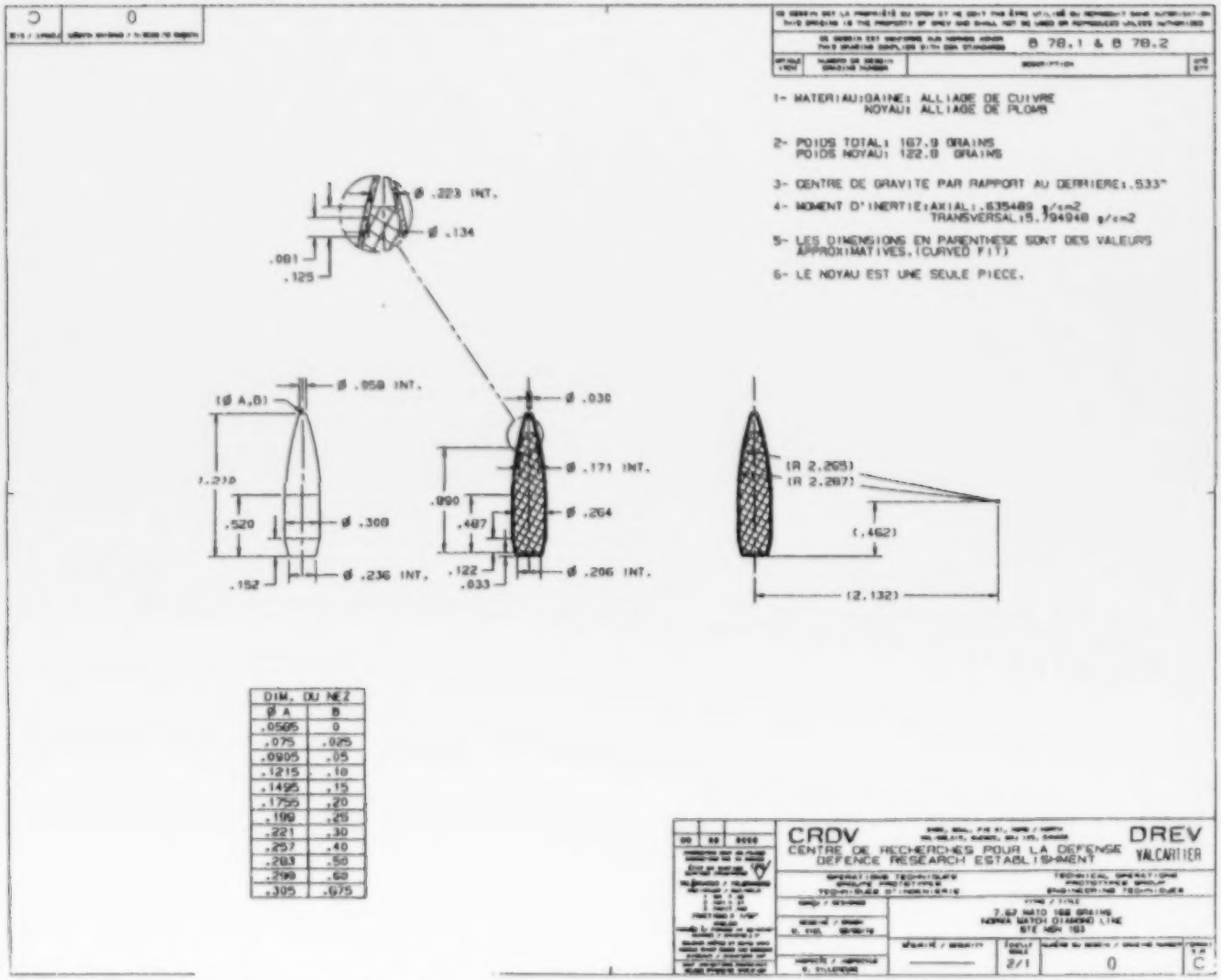

FIGURE 9 – Drawing of Norma 308 Win Match 168gr. Diamond

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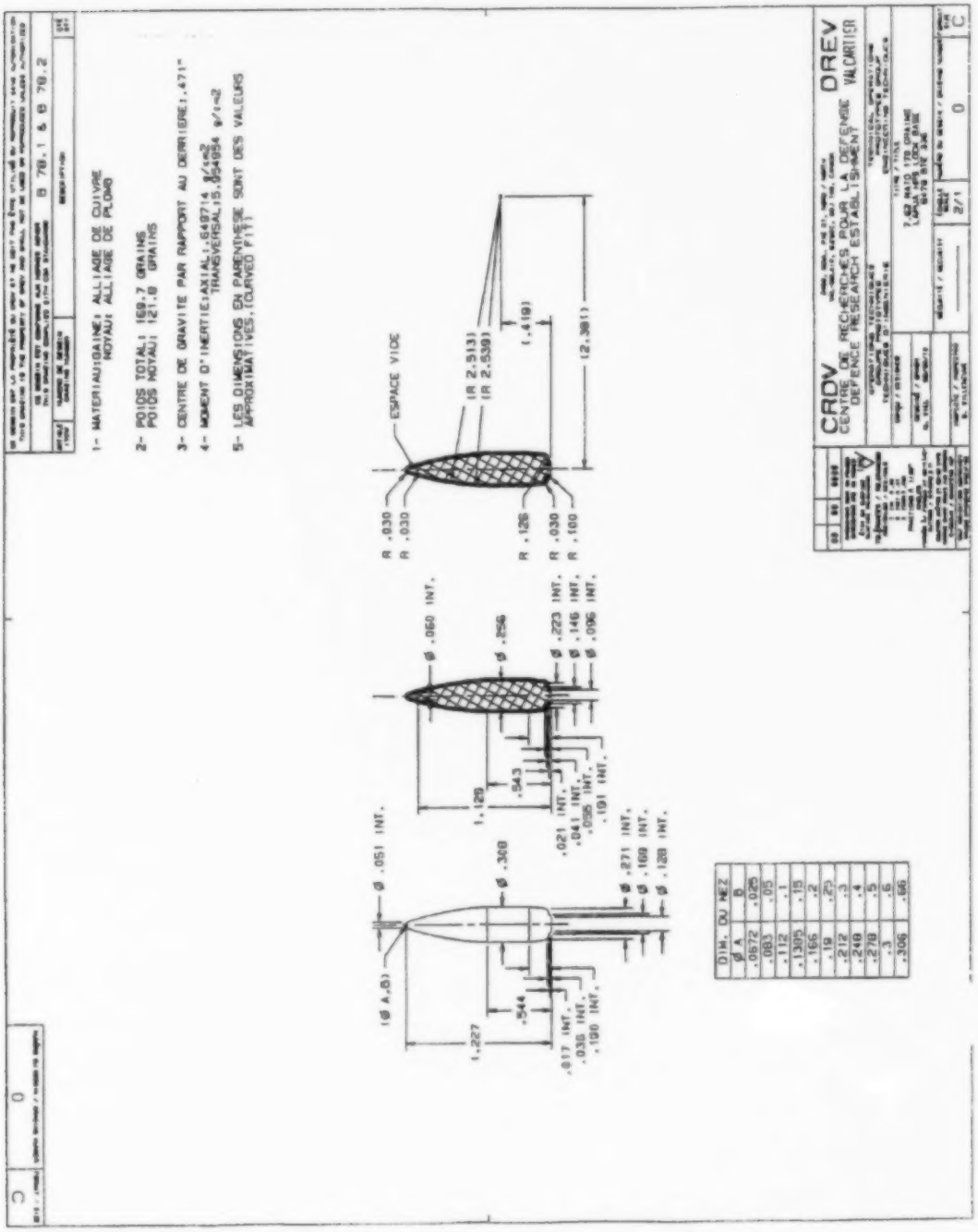
1- MATERIAU(GAINE): ALLIAGE DE CUIVRE
NOYAU: ALLIAGE DE PLOMB
2- POIDS TOTAL: 169.7 GRAINS
POIDS NOYAU: 121.8 GRAINS
3- CENTRE DE GRAVITE PAR RAPPORT AU DERRIERE: .471"
4- MOMENT D'INERTIE: AXIAL: .648714 g/cm2
TRANSVERSAL: 15.854954 g/cm2
5- LES DIMENSIONS EN PARENTHESE SONT DES VALEURS APPROXIMATIVES. (CURVED FIT)
ESPACE VIDE
CROV
CENTRE DE RECHERCHES POUR LA DEFENSE
DEFENCE RESEARCH ESTABLISHMENT
DREV
VALCARTIER

DIM. DU NEZ	
ø A	B
.0672	.025
.083	.05
.112	.1
.1305	.15
.166	.2
.19	.25
.212	.3
.240	.4
.270	.5
.3	.6
.306	.66

FIGURE 10 – Drawing of .308 Win HPS Lock base 11g B476

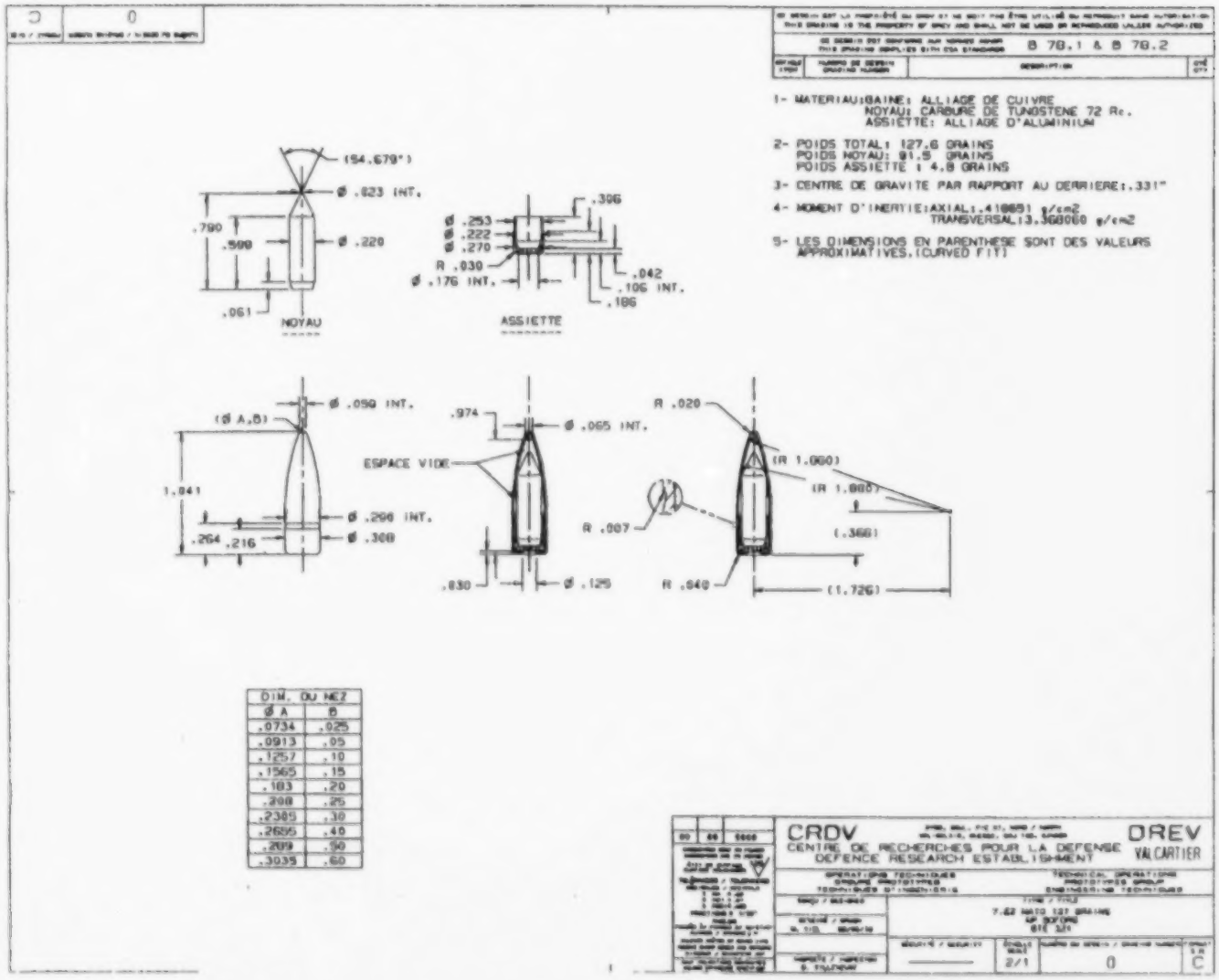

FIGURE 11 – Drawing of 7.62mm AP Bofors Carl Gustaf (M993)

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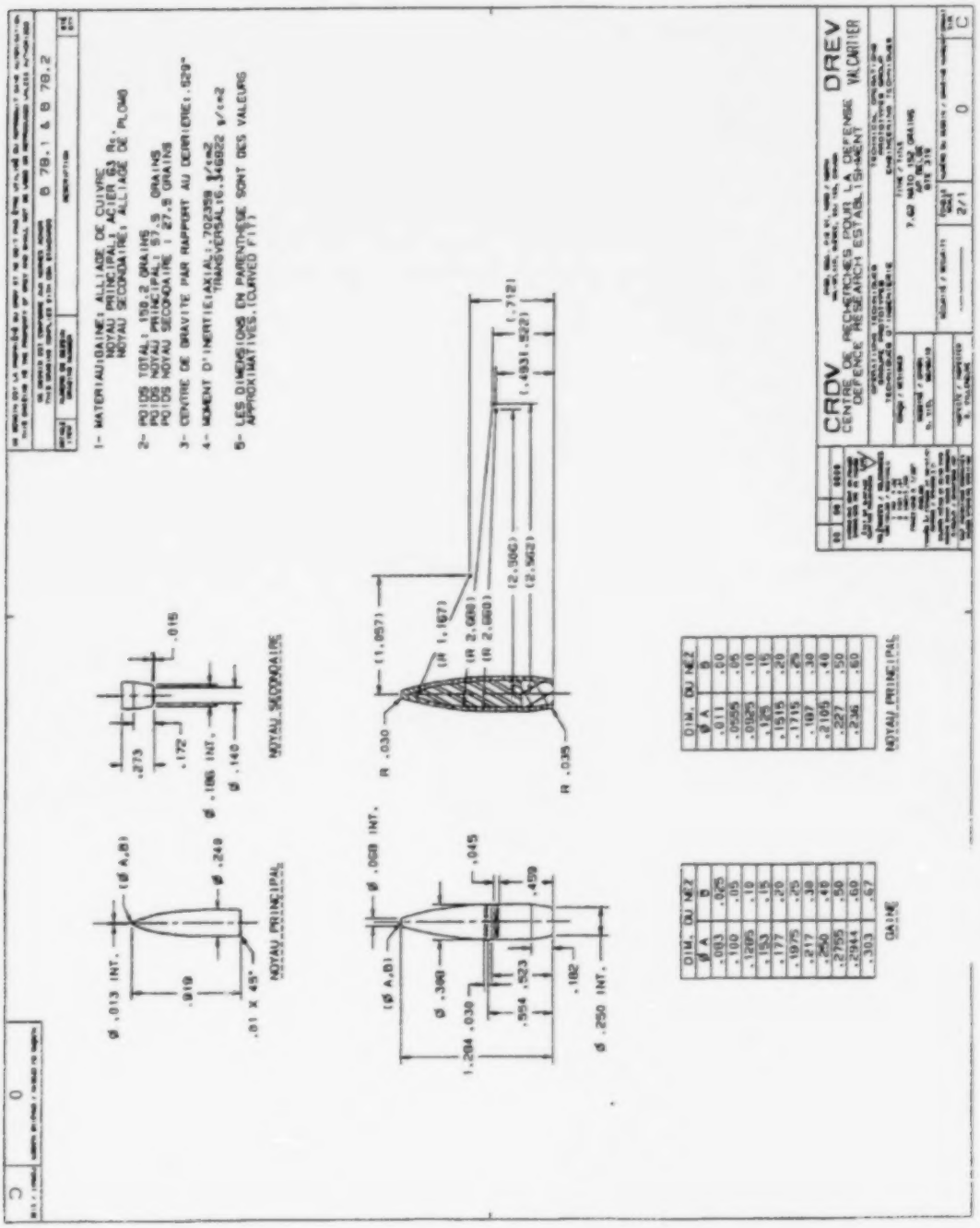
1- MATERIAU/GAINE: ALLIAGE DE CUIVRE
NOYAU PRINCIPAL: ACIER
NOYAU SECONDAIRE: ALLIAGE DE PLOMB
2- POIDS TOTAL: 199.2 GRAINS
POIDS NOYAU PRINCIPAL: 97.5 GRAINS
POIDS NOYAU SECONDAIRE: 27.5 GRAINS
3- CENTRE DE GRAVITE PAR RAPPORT AU DERRIERE: .529"
4- MOMENT D'INERTIE(AXIAL): .702359 g/cm2
TRANSVERSAL: 16.346822 g/cm2
5- LES DIMENSIONS EN PARENTHESE SONT DES VALEURS APPROXIMATIVES. (CARVED FIT)
CROV
CENTRE DE RECHERCHES POUR LA DEFENSE
DEFENCE RESEARCH ESTABLISHMENT
DREV
VALCARTIER
NOYAU SECONDAIRE
NOYAU PRINCIPAL
GAINE
DIM. DU NEZ

FIGURE 12 – Drawing of AP P80 7.62 mm NATO

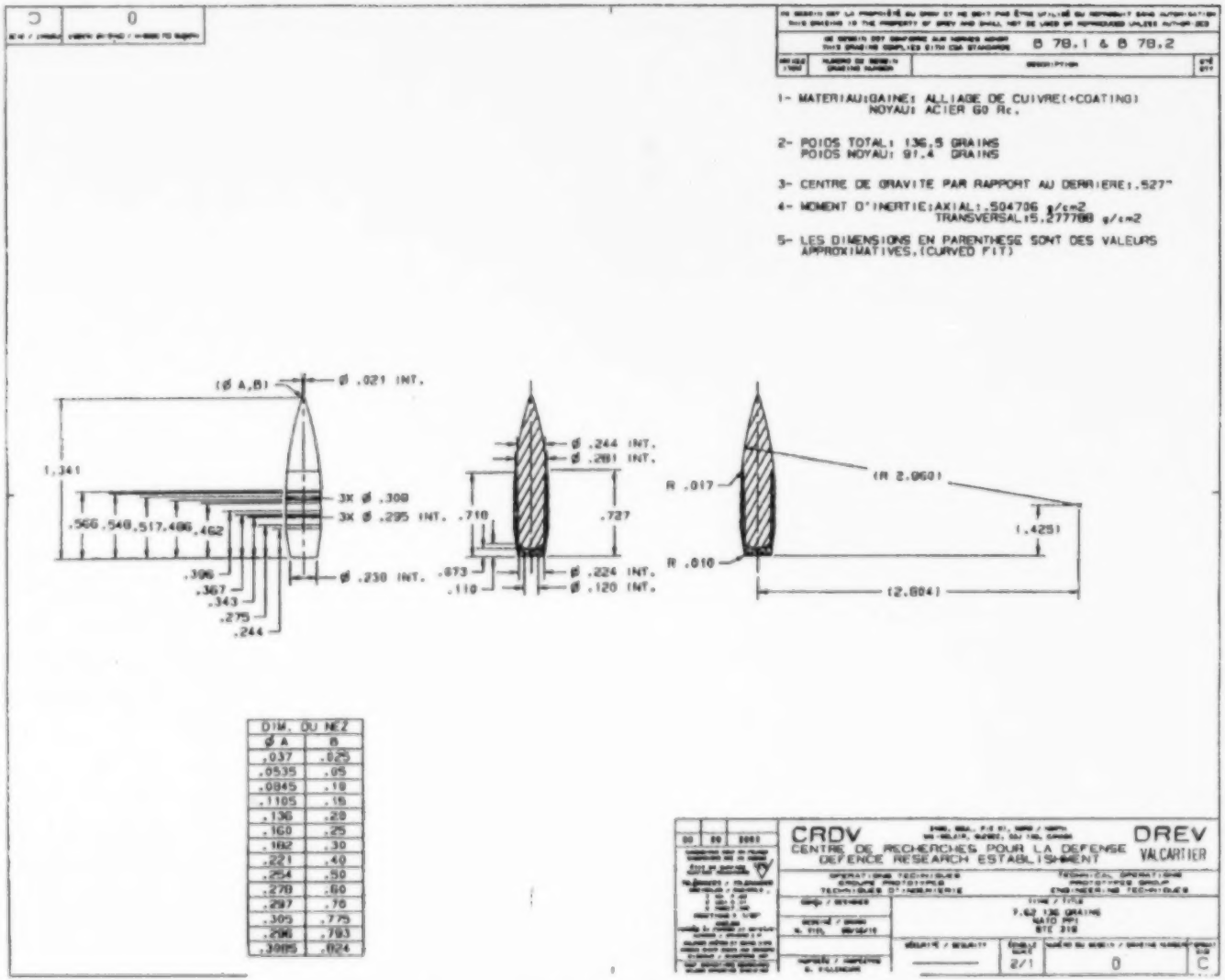

FIGURE 13 – Drawing of Anthena PPI 7.62 mm NATO

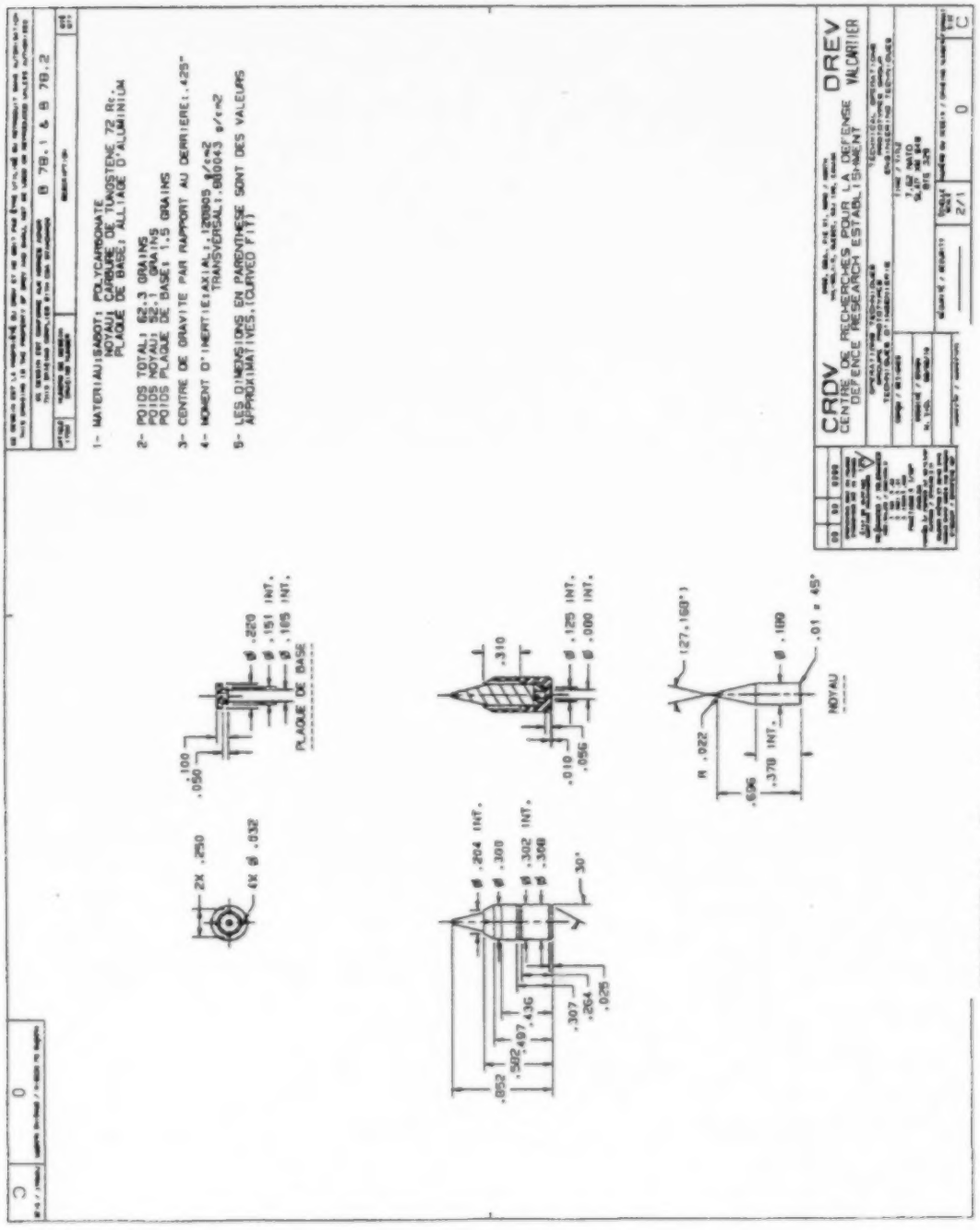

FIGURE 14 – Drawing of 7.62mm SLAP XM948

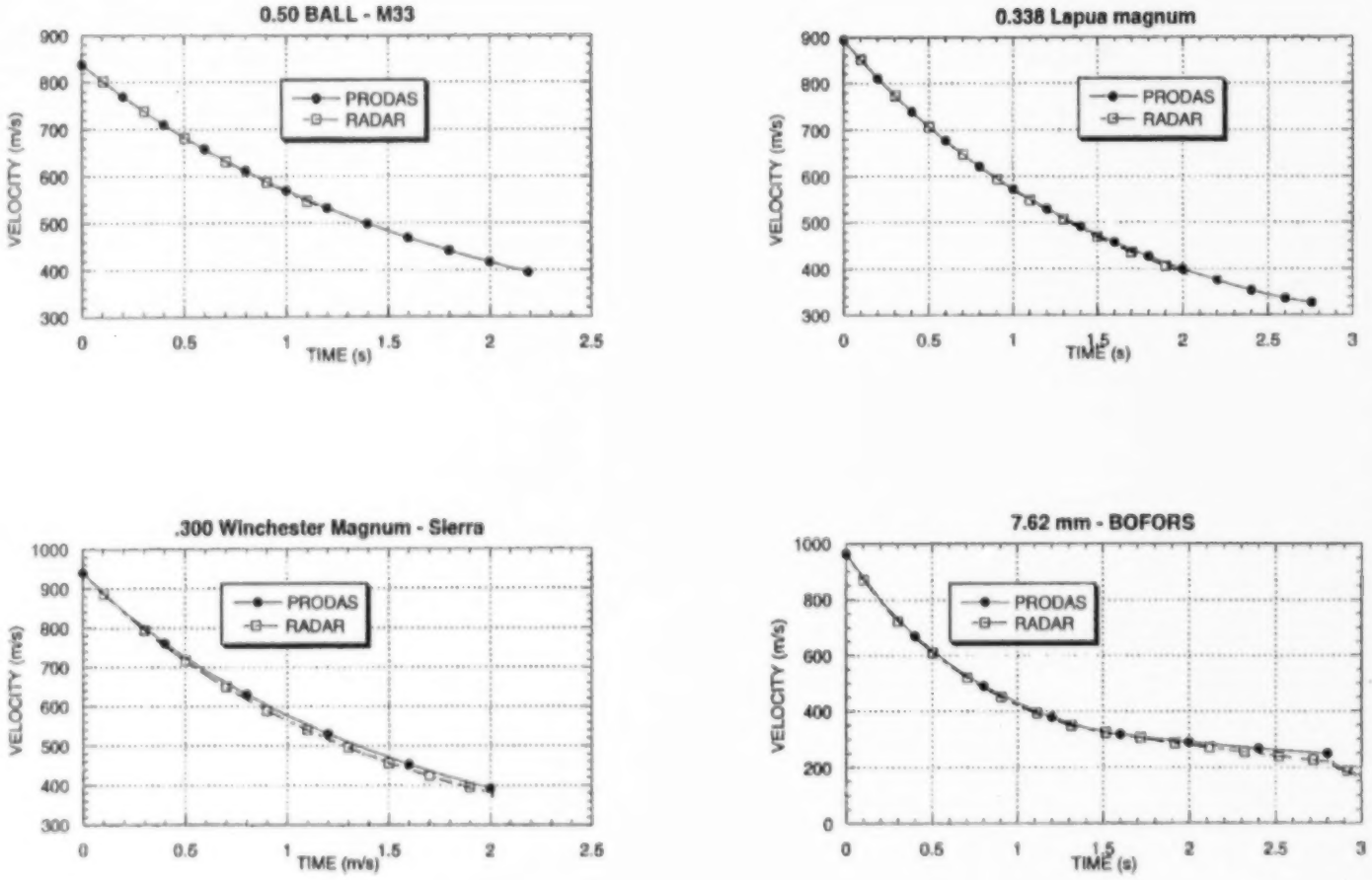

FIGURE 15 – Comparison of velocity profiles obtained by PRODAS and radar measurements; M33, .338 Lapua Magnum, .300 Winchester Magnum Sierra, AP Bofors

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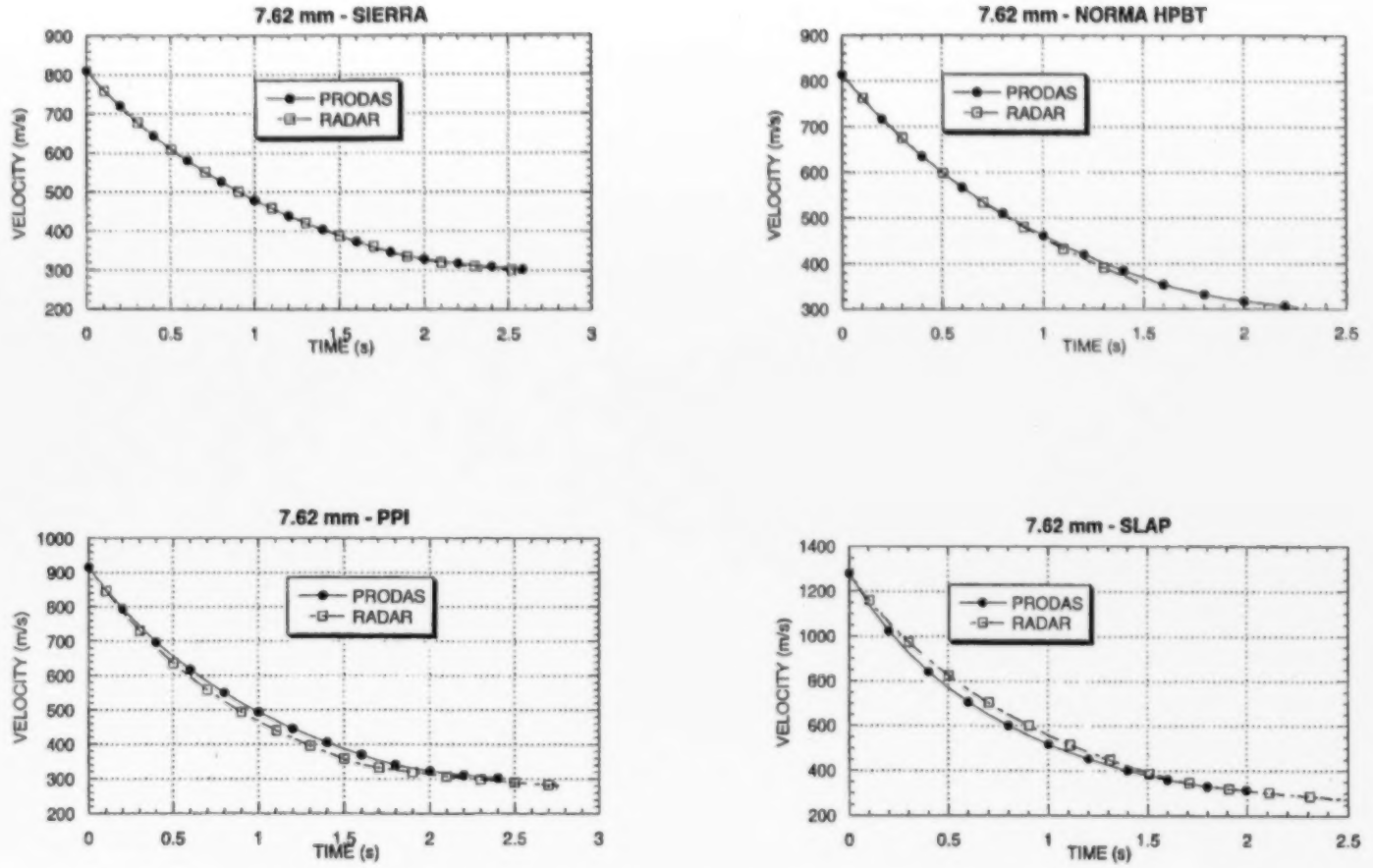

FIGURE 16 – Comparison of velocity profiles obtained by PRODAS and radar measurements; Sierra, Norma HPBT, PPI and SLAP

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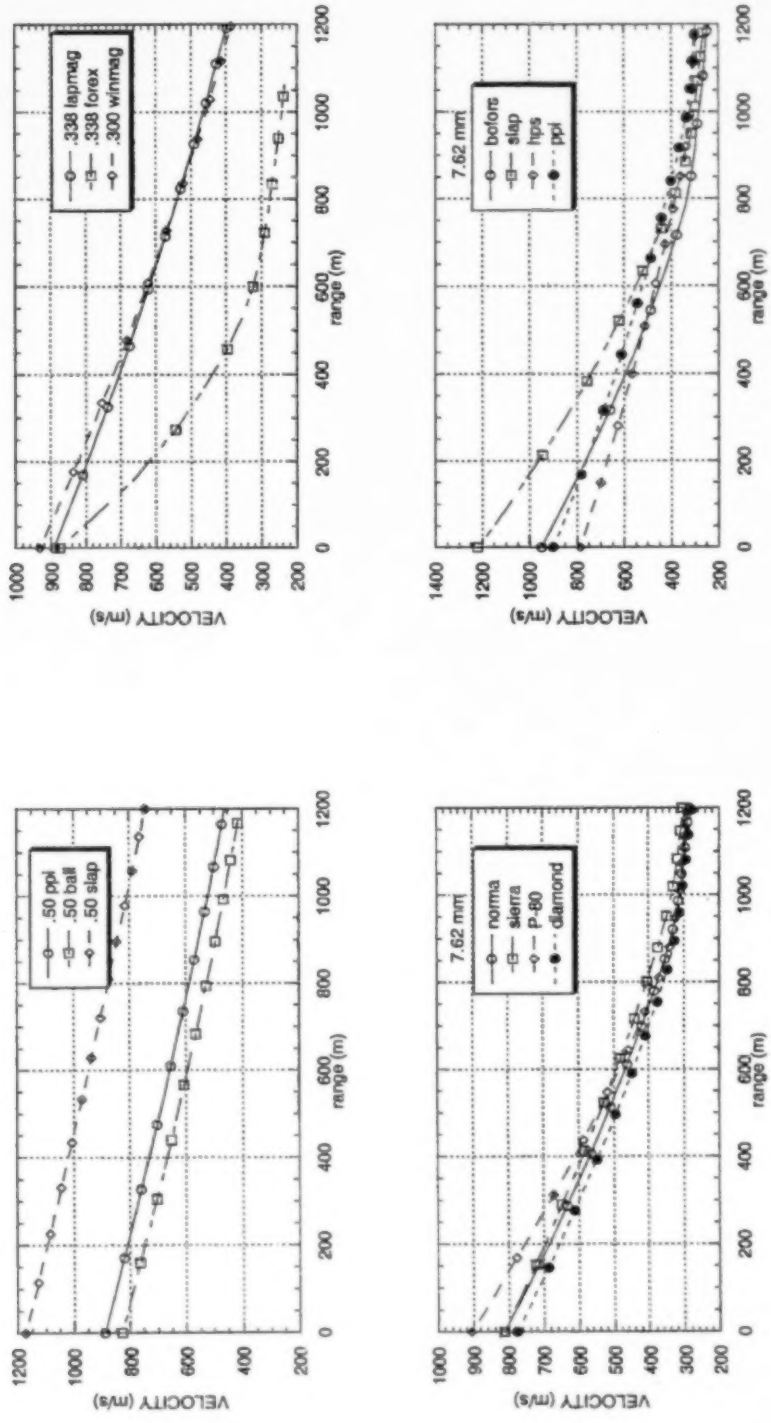

FIGURE 17 – Velocity versus range – 14 projectiles

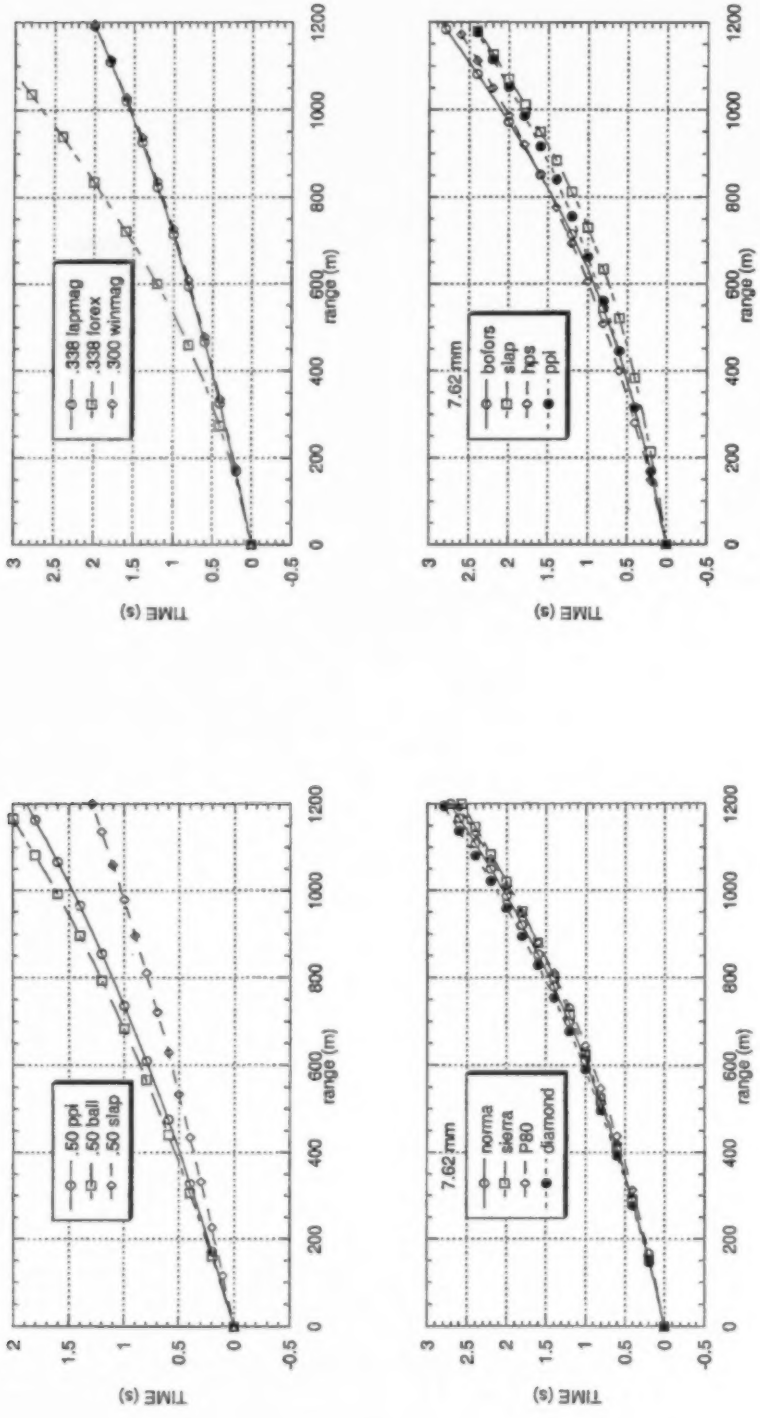

FIGURE 18 – Time of flight versus range – 14 projectiles

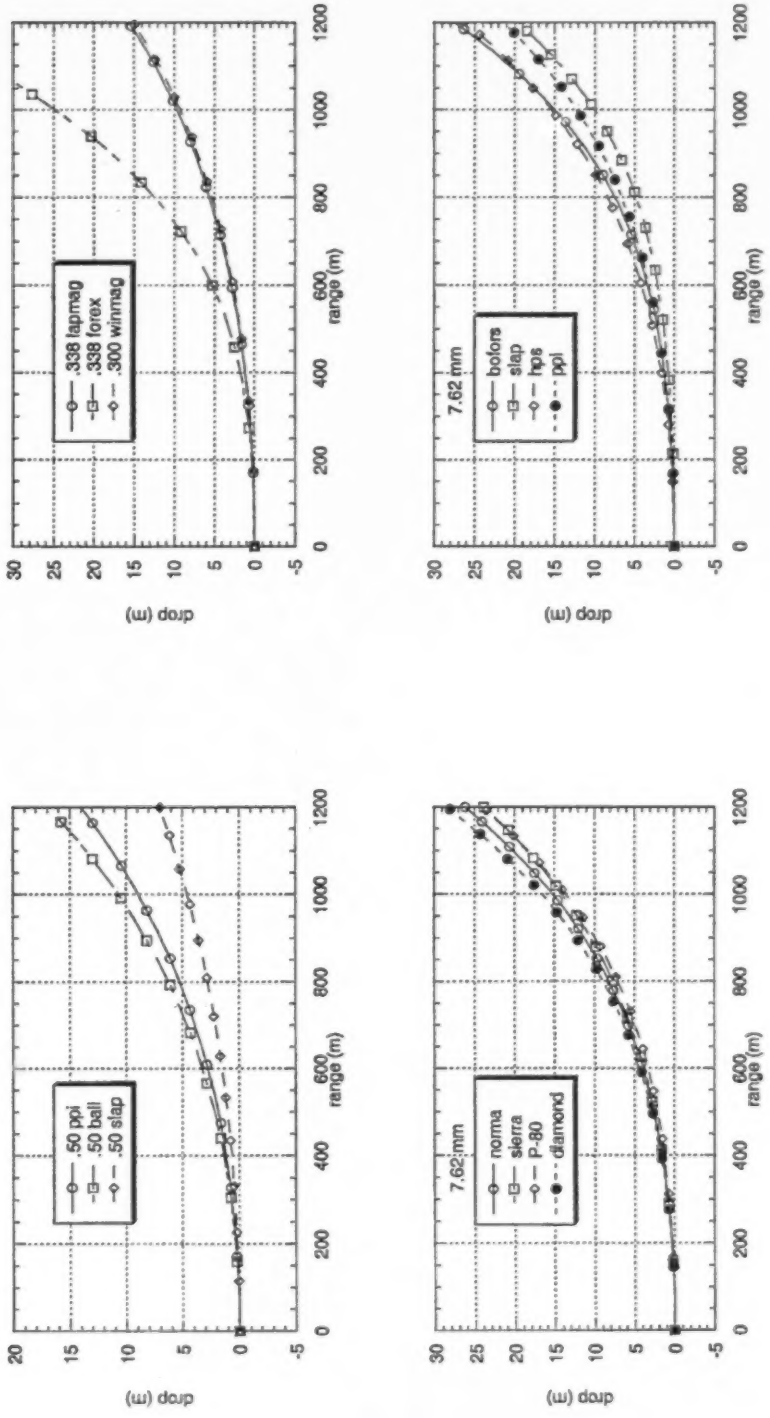

FIGURE 19 – Gravity drop versus range – 14 projectiles

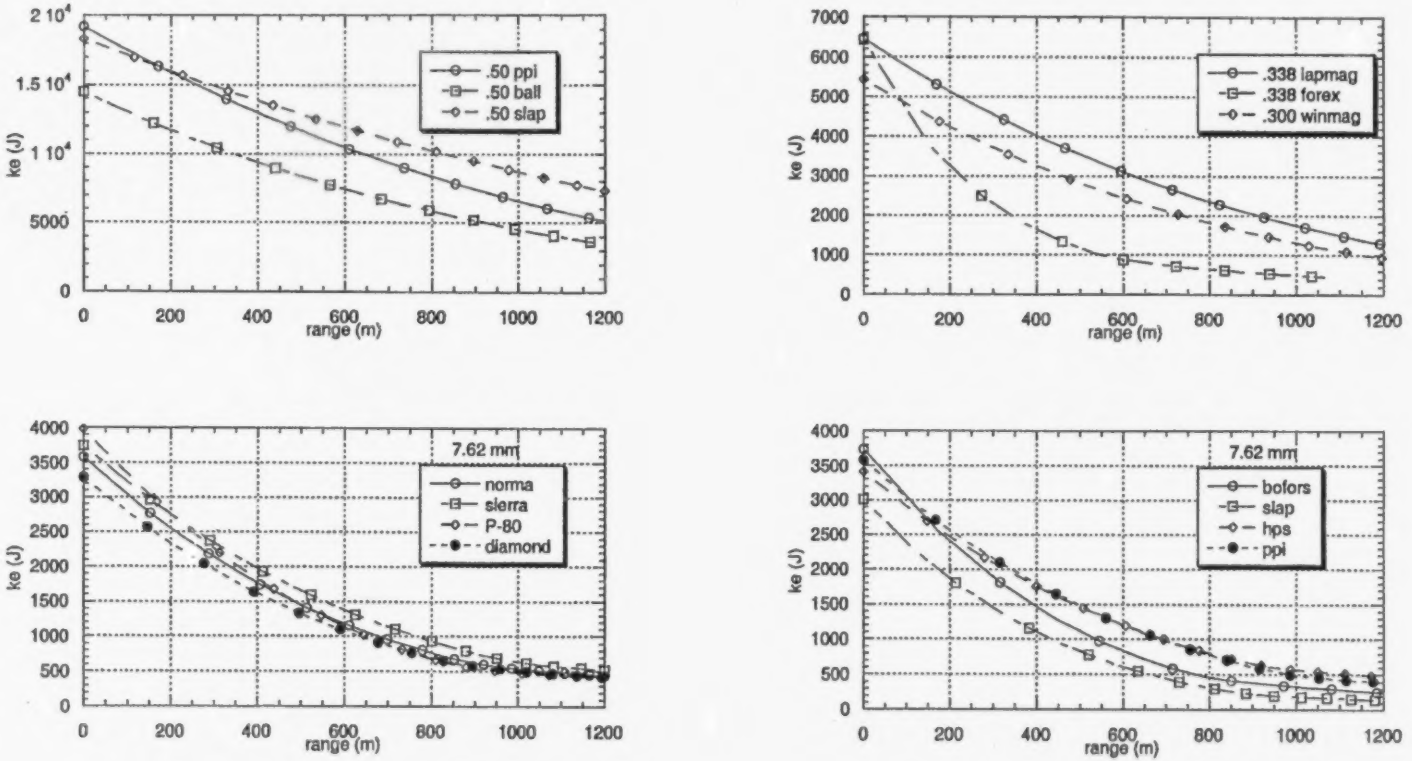

FIGURE 20 – Kinetic energy versus range – 14 projectiles

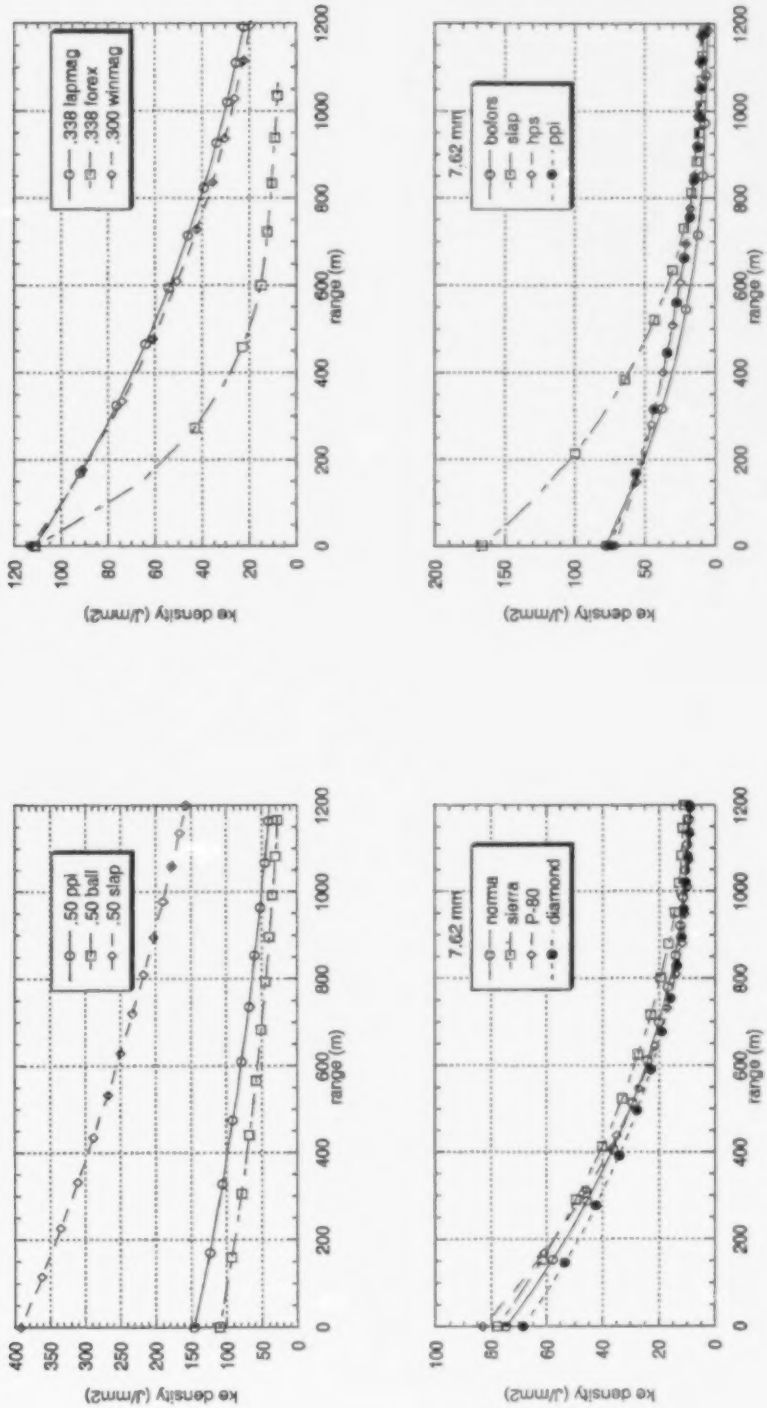

FIGURE 21 – Density of kinetic energy versus range – 14 projectiles

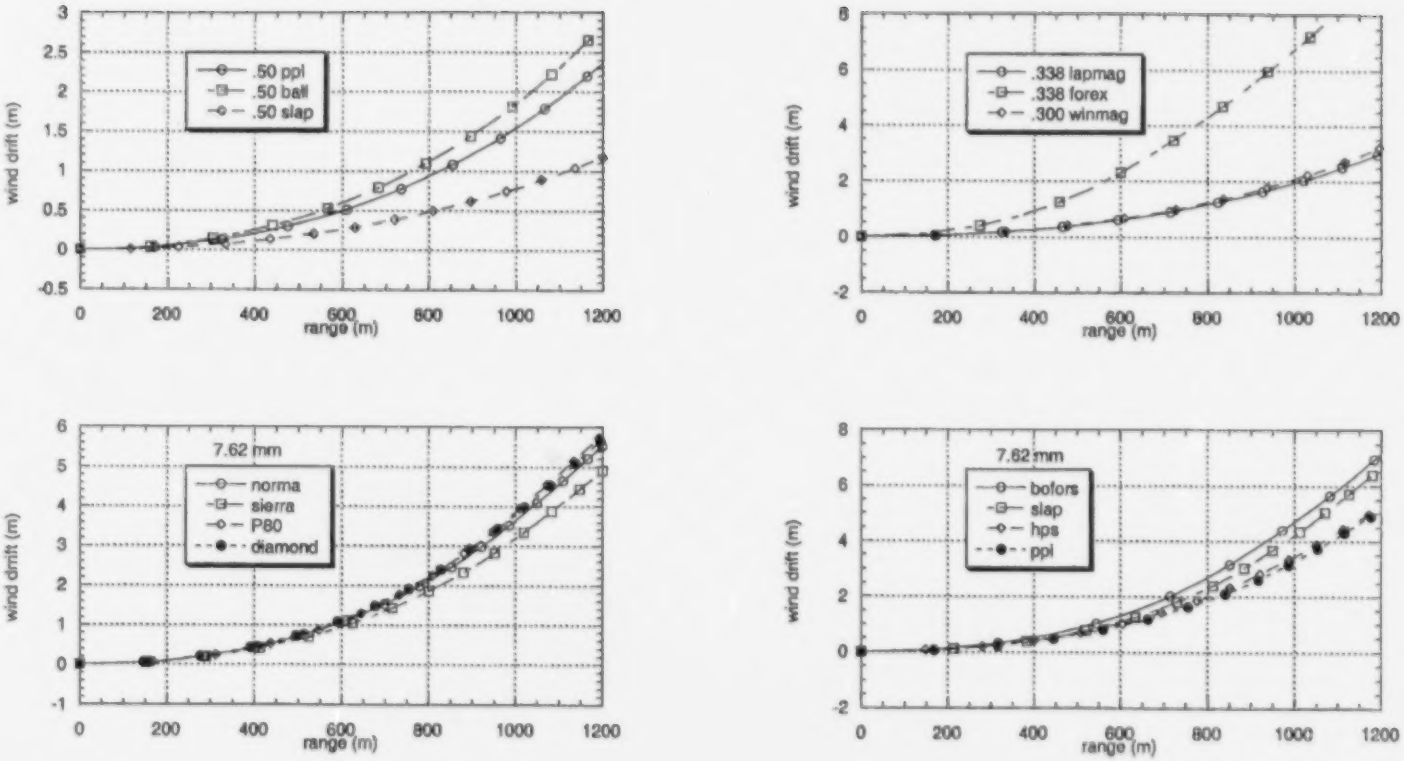

FIGURE 22 – Wind drift (wind of 4.47 m/s) versus range – 14 projectiles

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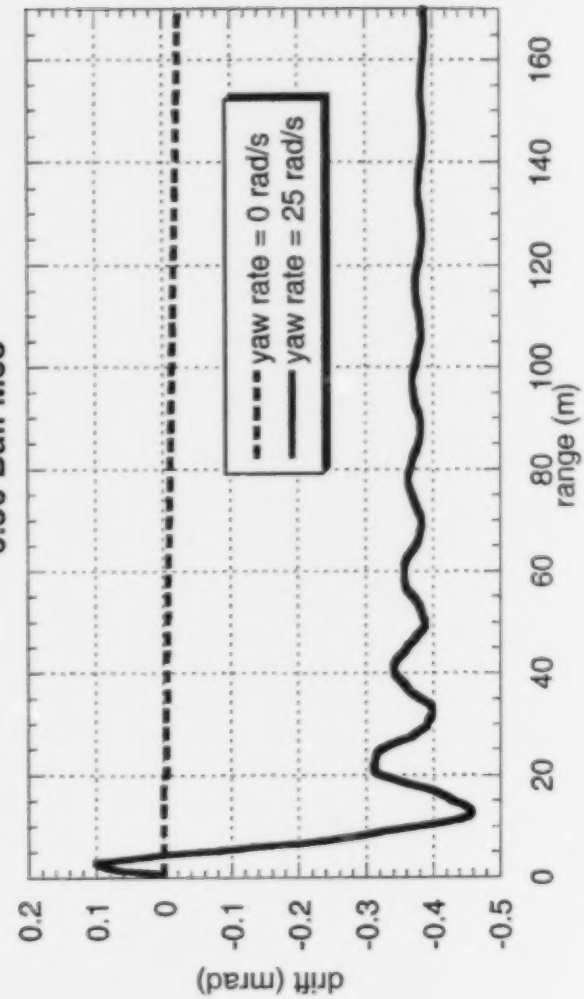

FIGURE 23 – Swerve motion of the 0.50 cal Ball M33 projectile

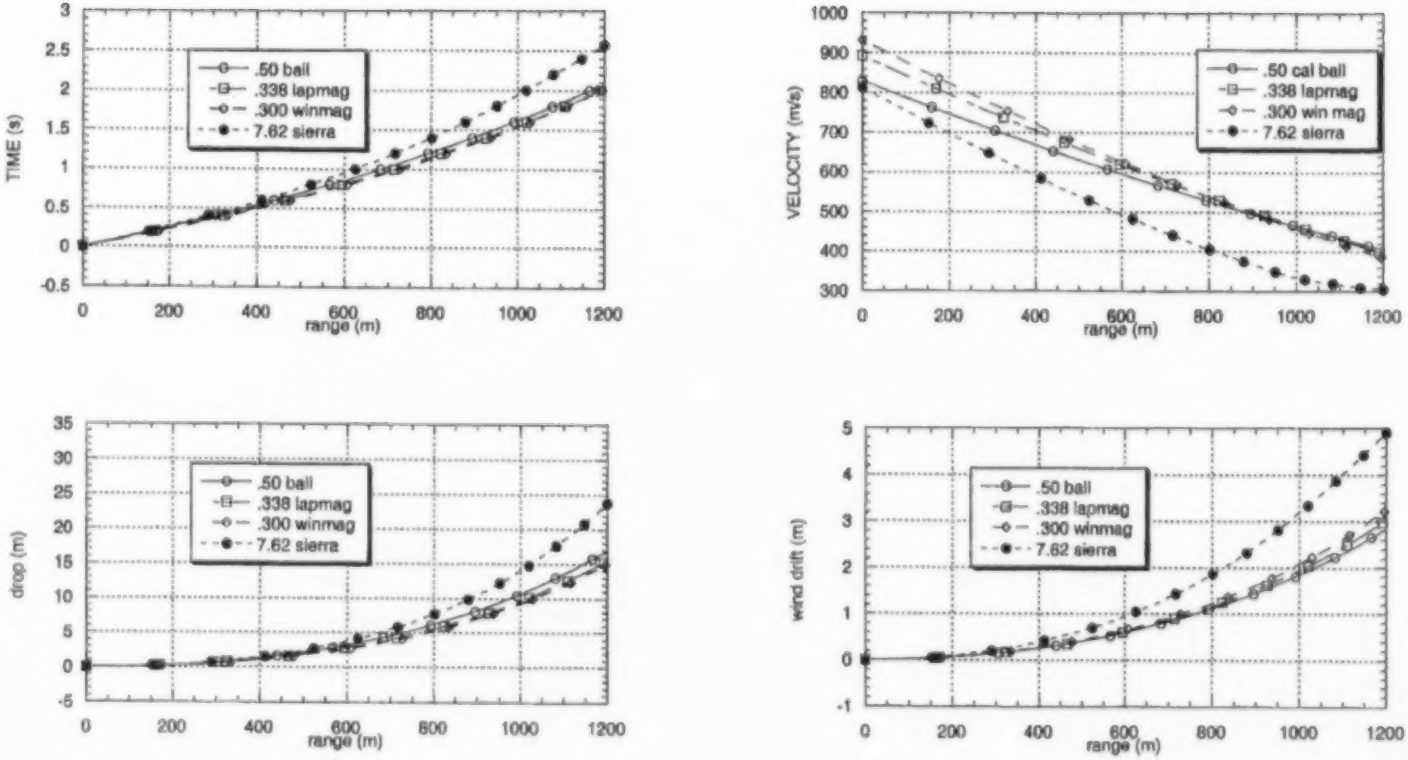

FIGURE 24 – Performance vs range for one projectile of each calibre; time of flight, velocity, gravity drop, wind drift (wind of 4.47 m/s)

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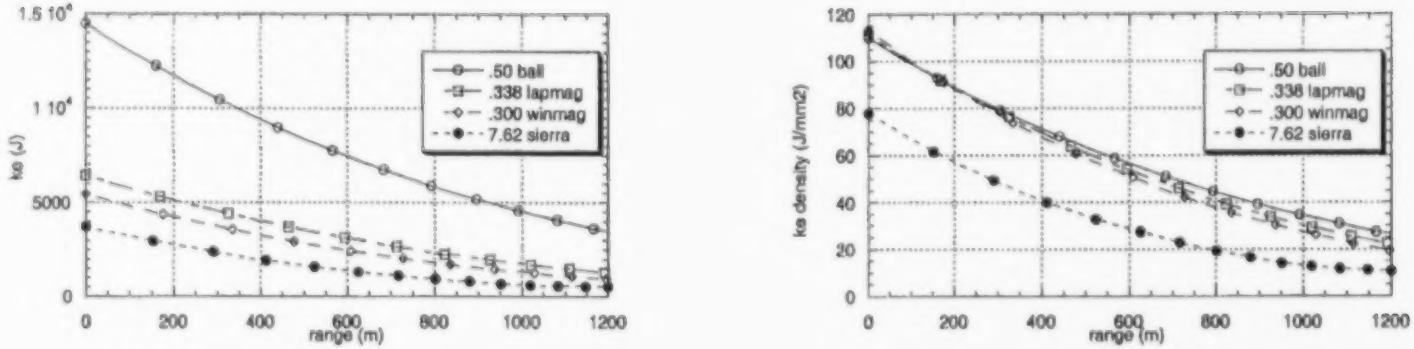

FIGURE 25 – Performance vs range for one projectile of each calibre; kinetic energy, density of kinetic energy

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The Directorate of Land Requirements (DLR) has requested the Defence Research Establishment Valcartier to carry out an investigation into the performance of various Heavy calibre sniper rifle systems. The objective of this part of the project is to establish with a common simulation methodology the performance aspects related to flight of a wide range of projectiles and to assess their relative importance. A total of fourteen projectiles distributed through four calibres (7.62 mm, .300 Winchester Magnum, .338 Lapua Magnum and 0.50 cal.) were investigated. The geometry and mass properties of the various projectiles were measured. Then, these results were used with the PRODAS software to obtain predictions of drop, velocity, kinetic energy, stability, and sensitivity to launch conditions and wind. These predictions indicated that the different design strategies used for the projectiles (combinations of inertial and aerodynamic properties) give different performance characteristics and that no single design gives the optimum characteristics for a sniper projectile at long range.

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